Tachyons and Other Things Fast: A Study of Superluminal Motion

A Major Qualifying Project Report
completed in partial fulfillment of the Bachelor of Science at
Worcester Polytechnic Institute

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Date:
April 2016

Abstract

This project examines two different types of superluminal motions. The first is of a theoretical particle known as the tachyon, whose existence is not forbidden by the laws of physics but which has never been observed. An interpretation of the interactions of tachyons with ordinary (subluminal) particles is given and a paradox involving tachyons is discussed. The second type of superluminal motion studied is connected with faraway galaxies. However the faster than light motion observed here is only apparent and can be understood on the basis of the known laws of physics. Data related to this effect is presented and analyzed.

1. Introduction

The idea of superluminal motion has been discussed ever since it became known that the speed of light is finite, even if very large. While neither special relativity nor Maxwell's equations expressly forbid superluminal solutions, the former does not allow massive objects to reach or surpass the speed of light because it would take an infinite amount of energy.

At first the idea of superluminal motion seems absurd because, according to special relativity, a particle moving at superluminal speeds would have an imaginary gamma factor and therefore an imaginary energy and momentum. However the energy and momentum of a particle are measurable quantities and so must always be real. This led many people to dismiss tachyons as absurd. However Sudarshan et. al [1], who were the first to popularize the idea of tachyons in the physics community, found a way found a way out of this quandary by letting the rest mass of a tachyon be imaginary, thus allowing the energy and momentum to become real again. The paradox of an imaginary mass was neatly sidestepped by the observation that one could never catch up with the tachyon to measure its rest mass.

In the half century since they were first proposed, tachyons have been investigated extensively by many physicists. An early and important paper by Feinberg [2] concluded that there was no argument against the existence of tachyons and convinced many physicists to take it seriously. Two early overviews of tachyons can be found in the non-technical articles by Feinberg [3] and Newton [4]. The causality effects of tachyons were examined by Newton [5], Parker [6] and Broido and Taylor [7], among others. Experimental searches for tachyons were carried out by several groups, such as [8], [9], [10] and [11], but without ever detecting one. A recent book by Gott [12] explores the role that tachyons and faster than light motion play in cosmology.

We introduce some terminology. We term particles with real mass $m^2>0$ and speed $v<c$ as bradyons; these cannot be accelerated to speeds greater than that of light. The tachyon, by contrast, is a particle with imaginary mass $m^2<0$ and speed $v>c$, which cannot be decelerated to a speed below that of light.

The paradoxes to be explored only arise if it is assumed that tachyons can be emitted, modulated and absorbed by bodies in the subluminal universe. If this were indeed to be possible, it would mean that we could establish a cause and effect relationship between two events separated by a space-like interval. This would lead to the paradox that the effect could precede the cause in some frames of reference.

This seemingly defies the laws of causality and therefore logic, but a closer look reveals it can be justified.

The first chapter of this report explains how the seeming violation of causality can be justified by the “Reinterpretation Principle” [1]. Following this, a paradox connected with tachyons [14,15] is presented both through a qualitative discussion based on a Minkowski diagram as well as through algebraic calculations based on a time sequence of events involving the transmission of tachyons between two subliminally moving (or bradyonic) observers. Possible resolutions of the paradox are then discussed.

The second problem we will explore is the apparent superluminal motion of certain distant galaxies. The paradox here is that these galaxies appear to move at speeds faster than that of light when their motion is viewed on the celestial sphere. There is a great deal of data as well as theoretical discussion on this topic [18], [19], [20]. This again seems to present us with a paradox, but it turns out that the paradox can be made to disappear by a perfectly straightforward analysis based on the known laws of physics. Chapter 2 of this report lays out the paradox and the reasoning that can be used to resolve it. Experimental data exhibiting the paradox are presented and it is shown how the resolution of the paradox can be used to glean useful information of the galaxies or other objects involved.

The overall goal of this project has been to look at some examples of superluminal phenomena and show that there is more here than meets the eye. Both the phenomena studied are very puzzling and perplexed physicists when they were first exposed. The first, tachyons, continues to be the subject of considerable discussion, and some controversy, even today. However the second, the apparently superluminal motion of distant galaxies, has been laid to rest.

The two examples of superluminal motion discussed in this report are by no means the only ones that have engaged the attention of physicists. Faster than light motion of various types of waves and particles in material media are being actively studied [21-23]. However they are beyond the scope of this report.

2. Paradoxes of the tachyon

Can tachyons be emitted, absorbed, and modulated from the subluminal universe? In order to determine this, we must consider all the paradoxes that come as we observe a superluminal particle. Let's consider a tachyonic particle moving through space at some speed *v>c*, as seen from an observer in a some inertial reference frame. According to relativistic mechanics, that particle's gamma factor:

$$\gamma = 1/\sqrt{1-(v/c)^2}$$

turns out to be an imaginary quantity, and therefore its energy and momentum:

$$E = \gamma\, m_0 c^2 \text{ and } p = \gamma\, m_0 v$$

are also imaginary. Since energy and momentum are always real, this forces the mass to be imaginary. This can be justified by understanding that the mass of this particle could never be measured, because nothing from the subluminal universe could ever catch up to it [1]. Therefore we define as $m_0 \equiv im$ where *m* is the unmeasurable "meta-mass" of the particle. Energy and momentum of a tachyon in real quantities are then defined as:

$$E = \gamma_r mc^2 \text{ and } p = \gamma_r mv$$

where

$$\gamma_r = 1/\sqrt{(v/c)^2-1}$$

We can use these to illustrate the fundamental difference between bradyons and tachyons. Figure #1 shows very clearly, using the equations above, how energy and momentum behave as speed changes.

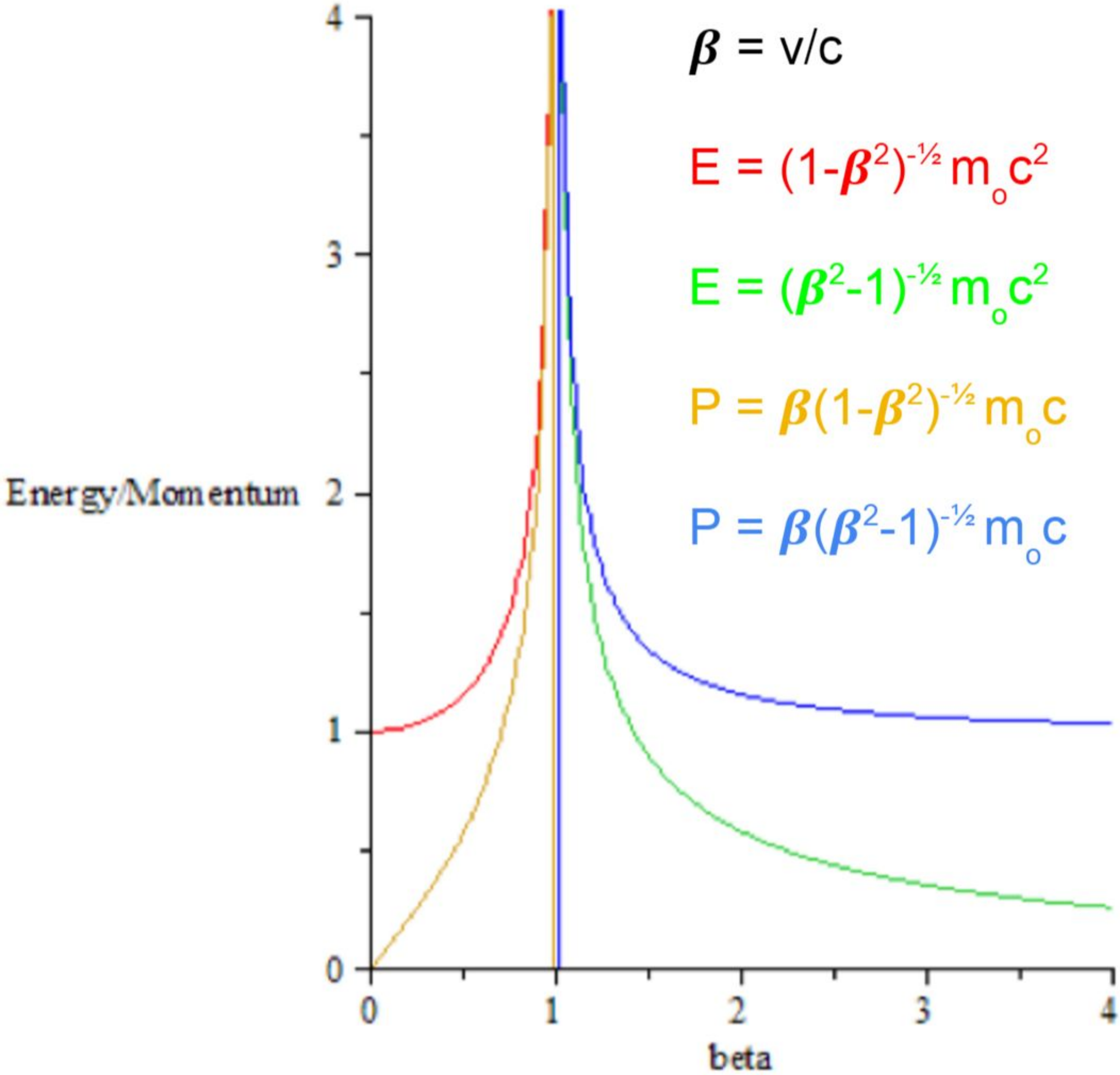


Figure #1: Energy/Momentum vs Speed (Energy in units of m_oc^2, Momentum in units of m_oc, speed in units of c.) We can see that as speed goes to zero, energy becomes the rest energy and momentum becomes zero. Meanwhile, for tachyons, as speed goes to infinity energy becomes zero and momentum goes to m_oc. Most importantly as the speed becomes c, everything goes to infinity.

Knowing this and using the previous results, let's consider a thought experiment with a tachyon interaction:

There are two observers in two frames of reference S and S', where S' moves along the x-axis with speed u with respect to S. Consider two events E1 and E2, the first one occurs at point A with coordinate x_1, the second one at point B with coordinate x_2. According to frame S, at time t_1 the source stationed at A emits a tachyon with speed v_1 (E1), and then at time t_2 it is absorbed by the observer in frame S' at the point B (E2).

In this experiment, two causally related events are connected by a space-like interval. Classically, this could never happen because a braydon, by definition, could never connect two events with a space-like interval, but a tachyon always will. This means that there is a frame of reference in which one would see these two events in the reverse time order [13], with an observer seeing the tachyon being absorbed before it is emitted. Let's say S' moves at a speed u that is fast enough to be such a frame, the observer in S' will then receive a tachyon before the observer in frame S emits that same tachyon. To find the conditions for this event reversal, we proceed as follows.

The tachyon's velocity in frame S is defined as:

$$v_1 = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}$$

In the frame S' this time interval between the emission and reception of the tachyon is:

$$\Delta t' = \gamma(\Delta t - \frac{u\Delta x}{c^2})$$

Event reversal will occur when $\Delta t'$ becomes negative. Since gamma is always positive, the condition becomes

$$\Delta t - \frac{u\Delta x}{c^2} < 0$$

Using some algebraic manipulations, the condition for time switch can be written as

:

$$\frac{\Delta x}{\Delta t} u = v_1 u > c^2 \,.$$

The apparent reversal of cause and effect challenges the whole idea of causality, to address the challenge, a reinterpretation of the events is in order.

2.1 The reinterpretation principle

As mentioned, there is a condition $uv > c^2$ that must be met for an observer to witness two causally linked events reverse. However this "switch" is not the only significant change that can be observed when the condition is met. Using the previously defined energy and momentum of a tachyon and the Lorentz transformations we can show what that energy appears to be in frame S'.

$$E' = \gamma(E - up)$$

Now the condition for E' to be negative is

$$E - up < 0$$

$$\gamma_r m(c^2 - uv) < 0$$

Thus we see that the same condition $uv > c^2$ accounts for both the event reversal and negative energy in the primed frame. We have established that if this condition is met, the observer in frame S' will receive a tachyon with negative energy at point B before the the observer in frame S emits a tachyon with positive energy at point A. From the point of an observer in frame S', the tachyon is emitted at point A with a negative energy **at a later time** than it is absorbed (with negative energy) at point B. This motivates the Reinterpretation Principle, which avoids the troubling concepts of backward time travel and negative energies by regarding **the absorption of a particle with negative energy as equivalent to the creation of a particle with positive energy** and **the creation of a particle with negative energy as equivalent to the absorption of a particle with positive energy [1].**

So when the observer at B "absorbs" the tachyon with negative energy, that energy drop can be interpreted instead as the emission of a tachyon with positive energy. Similarly at point A, the surge in power from emitting a tachyon with negative energy can be interpreted as receiving a tachyon with positive energy. The whole process can then be viewed as an emission of a particle with positive energy at B followed by its absorption at A at a later time. Note that the time sequence of events is the opposite of what it is in frame S.

2.2 Yoshikawa's paradox

While the reinterpretation principle solves the event reversal paradox, it also creates another. This paradox was established in different formats by different authors, but Yoshikawa's letter boils it down to a truly interesting paradox.

Let's go back to the same problem, but imagine two more events. Events two and three happen simultaneously, the latter is the observer at B sending a second tachyon with speed v_2' (as seen from S') back towards A. This observer has been instructed to send the second tachyon only when he receives the first one. The fourth event is the observer at A receiving the second tachyon.

As we know from the reinterpretation principle, the observer at B will see a tachyon being emitted towards A with speed v_1', and at the same time, the observer at B will send out a second tachyon with speed v_2'>v_1' towards A. This results in the second tachyon reaching A before the first one does [14]. If the observer at A is told to release his tachyon (the first tachyon) only after he sees the second tachyon being emitted towards B, then we have a causal 'loop'.

In other words, the observer at A is told to release his tachyon only if he sees the other tachyon, which the observer at B will only release when he sees the first tachyon. **Therefore the observer at A must release his tachyon in order to receive the signal that tells him to release that same tachyon.**

We can analyze this algebraically, event by event. Table #1 shows the coordinates of each event as seen from frames S and S', with the coordinates in the two frames being related by the standard (subluminal) Lorentz transformations.

	Coordinates as seen from S	Coordinates as seen from S'
E1	$(x_1, t_1) = (0, t_1)$	$(x_1', t_1') = (-u\gamma t_1, \gamma t_1)$
E2	$(x_2, t_2) = (\frac{uv_1t_1}{v_1-u}, \frac{ut_1}{v_1-u})$	$(x_2', t_2') = (0, \frac{v_1t_1}{\gamma(v_1-u)})$
E3	$(x_2, t_2) = (\frac{uv_1t_1}{v_1-u}, \frac{ut_1}{v_1-u})$	$(x_2', t_2') = (0, \frac{v_1t_1}{\gamma(v_1-u)})$
E4	$(x_3, t_3) = (0, \frac{t_3'}{\gamma})$	$(x_3', t_3') = (\frac{-uv_2't_2'}{v_2'-u}, \frac{v_2't_2'}{v_2'-u})$

Table #1 Event as seen from each frame

This paradox was neatly illustrated by Yoshikawa using a Minkowski diagram. Fugere #2 is the said diagram, with black lines for frame S and red ones for frame S'. The dotted lines with arrows represent the two tachyons, It can be seen that the second tachyon arrives at A (event C in the diagram) before the first tachyon is emitted (at the origin of the axes) [14].

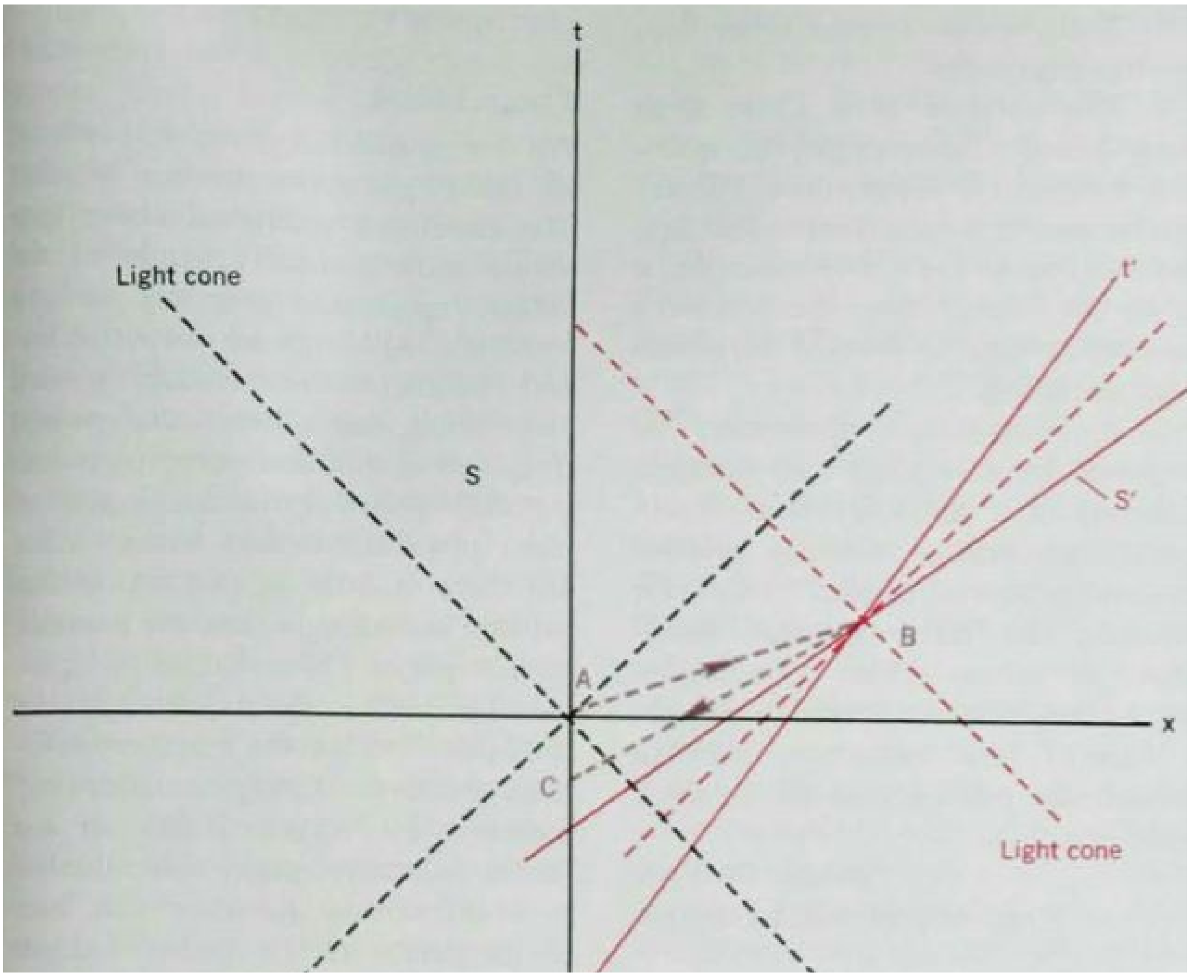


Figure #2: Yoshikawa's paradox illustrated. Event C is the direct effect of event A, yet event C precedes event A [14].

2.3 The anti-telephone and uniqueness of information

The previous analysis shows that tachyons can literally be sent into the past. If we consider tachyons being sent in the form of modulated beams (if that is possible!), it is possible to conceive of a machine that would send information into the past [15]. Figure #3 shows how modulated tachyon beams can send information to the same place back in time.

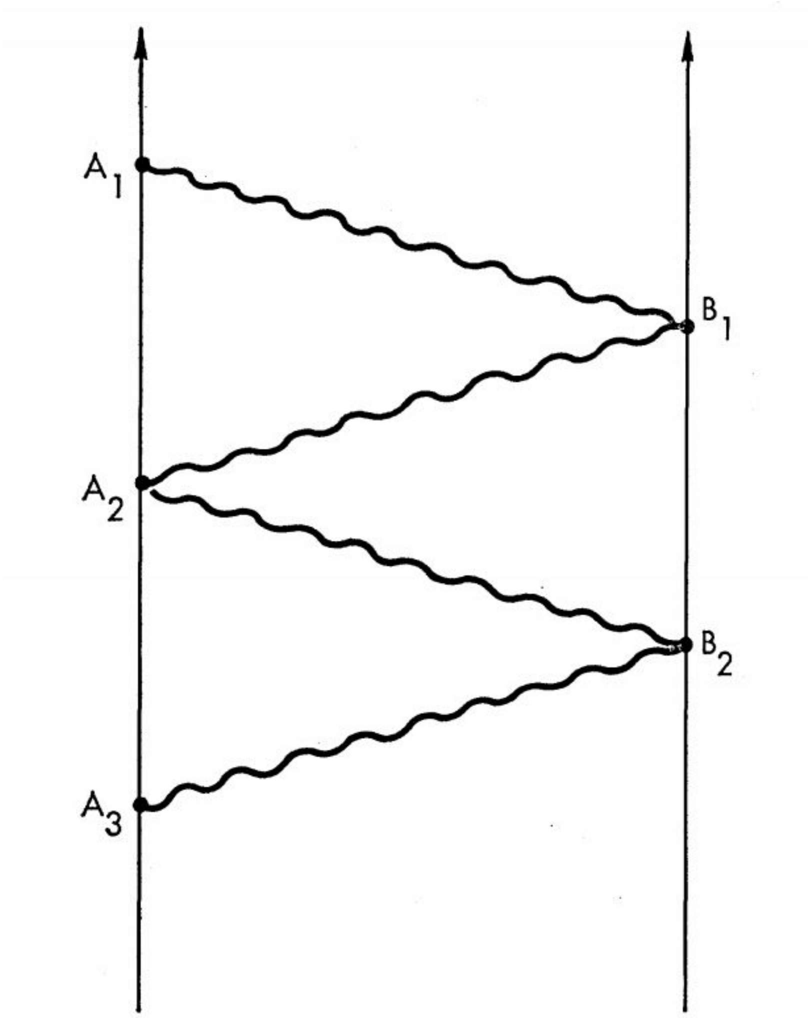


Figure #3: This shows how a stationary source at A and a moving source repeatedly arriving at B could send modulated beams back in time. [15]

This of course would lead into some irreconcilable comic book style time travel paradoxes, and while there have been attempts to reconcile this idea [17], there is no widely accepted solution.

The most fundamental problem with the antitelephone is that it would imply that information is not unique. If an author or poet could modulate a tachyon beam and send their work (which is unique) to an observer who receives the message before the artist has written it, who is then creating the message? **How can information exist before it is created? Furthermore, is there no room for free will? Do we not have the choice to change that message after it's been received but before it's been sent?**

2.4 The nature of time according to tachyons

There are several resolutions we can think of to these paradoxes, and here are some of them.

1. Tachyons can never interact with the subluminal universe.

2. The universe is so finely tuned that information from the future is somehow made irrelevant or wiped from the receiver's memory until all paradoxes are prevented [15].

3. The perception that only the present exists is false. We can look at time more like a spacial coordinate, one that can be travelled in both directions. This, of course immediately interferes with the idea of free will and constructs the universe as a completely deterministic.

3. Superluminal quasars

There are more than a few sets of images from far-away radio galaxies that show some components or ‘clouds’ moving (with respect to other clouds) at superluminal speeds. This is not allowed by the known laws of physics, and we will analyze the these images and explain why they appear to be moving so fast.

There are two very well-known examples which we will analyze, and they concern the radio galaxies 3C345 [18] and 3C279 [19]. By using the observed Doppler shifts we can find their recession velocity and hence their distance from Earth. From that we can determine their apparent speed on the celestial sphere (transverse velocity) as seen from Earth.

It is important to point out that the actual speed of these clouds can’t be known exactly; their apparent speed will become superluminal only for a certain threshold of angles at which that cloud approaches earth, and the faster the real speed of the cloud is, the larger that threshold becomes.

3.1 Derivation of the formula

Let’s analyze this situation algebraically. We want an expression that will define the transverse (apparent) velocity as a function of the actual velocity and the angle at which the cloud is moving with respect to our line of sight. Figure #4 shows the situation we are looking at.

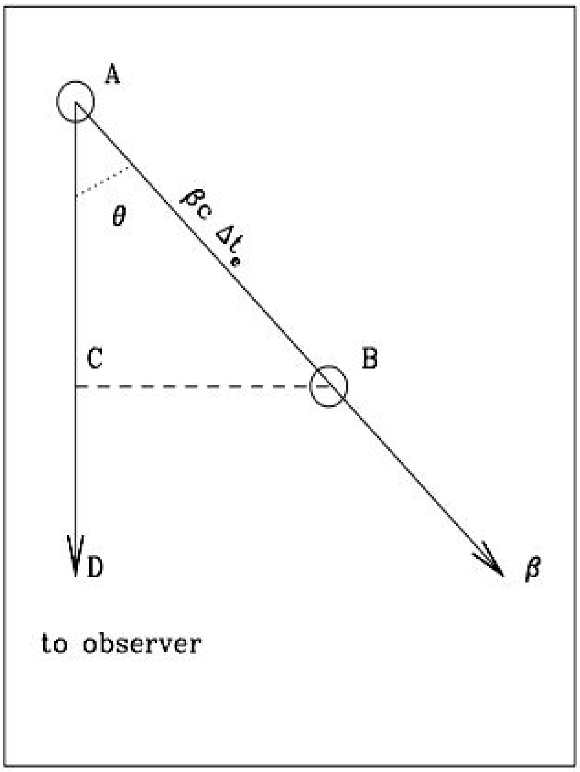


Figure #4: Cloud moving from A to B [20].

The cloud emits a photon at point A and another at point B. If it takes a time Δt_e for the cloud to move from A to B, then distance AB is the speed of the cloud (V) times the time period Δt_e. By geometry we find that the distance AC is then $V*\Delta t_e*\cos\theta$.

In this same time interval Δt_e, the photon released at A has reached D, and so the distance AD is equal to $\Delta t_e c$. The photon released at B will be behind the one released at A by a distance CD. That means the time interval we observe between the two photons is equal to the distance CD divided by the speed of the photon. That time interval is (with the simplified notation Δt_e=T):

$$CD/c = (AD - AC)/c = [cT - VT\cos(\theta)]/c = T(1 - (V/c)\cos(\theta))$$

The apparent distance travelled in this time interval is simply CB, which equals $V*\Delta t_e*\sin\theta$. From this we can find the transverse component V simply by dividing the distance CB by the time interval, CD/c, in which this distance appears to be covered. This gives us the following equation for the transverse speed V_T:

$$V_T = \frac{V\sin(\theta)}{1-(V/c)\cos(\theta)}$$

3.2 Understanding the formula

It will be easy to understand the mechanics of this illusion once we graph the values of transverse speed vs the angles of motion for different values of the real V.

Let's show how these values are spread. First we find out what is the minimum real speed of a cloud so that its transverse speed is superluminal. This will happen at a specific angle.

Figure #5 shows the apparent speed of a cloud as a function of the angle of motion.

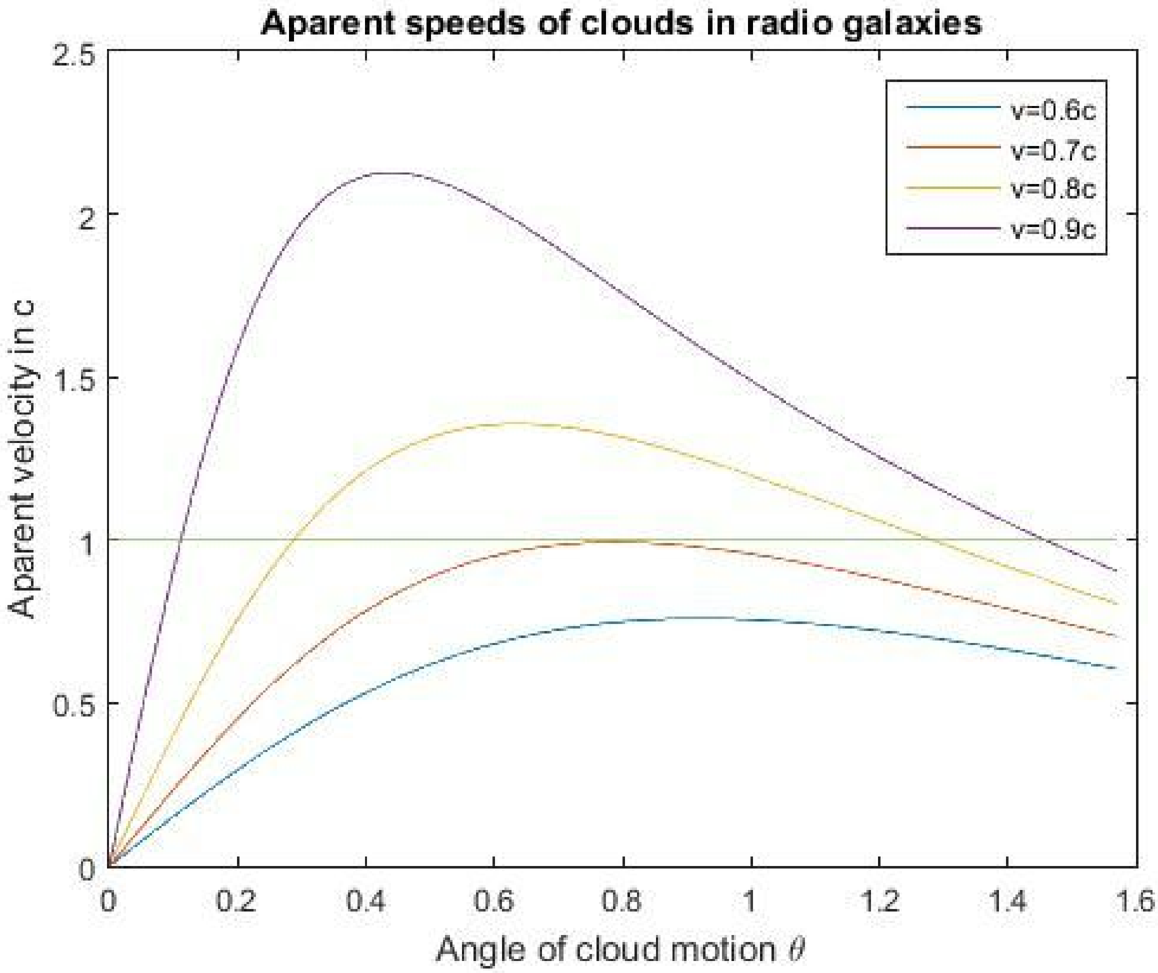


Figure #5: Each line represents a real speed V. It is clear that the larger the real speed is, there are more angles for which the transverse speed will appear superluminal. We can observe that the minimum real speed to achieve an apparently superluminal motion is close to 0.7c. It is also worth noting that as the angle becomes zero, V_T becomes zero, since it is moving directly towards earth.Similarly when the angle becomes $\pi/2$, V_T becomes V, since it's movement is perpendicular to our line of sight.

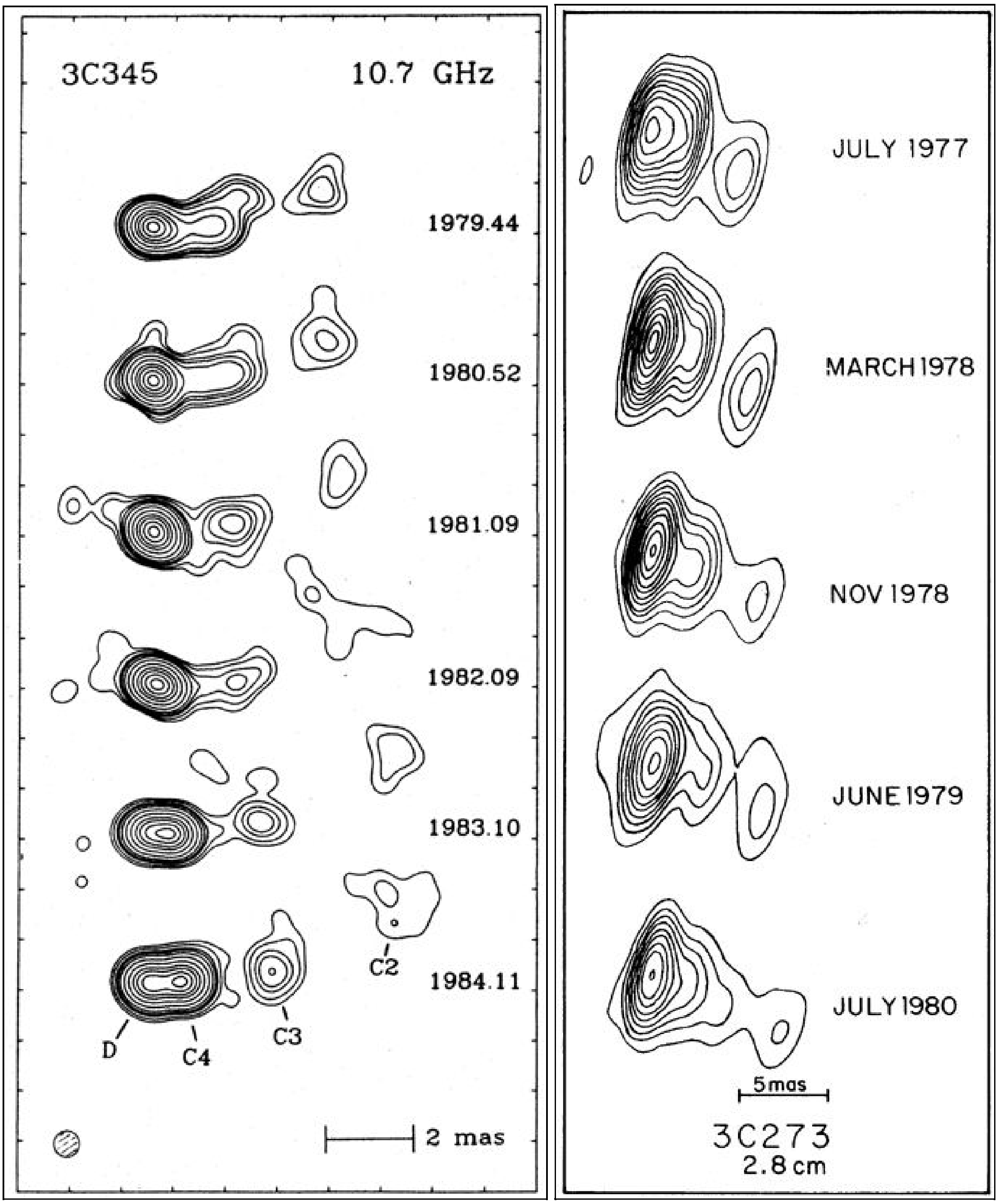
In figure #5 one can see that for a speed of V=0.7c there is a single angle at which the cloud must advance to appear to move at c. For larger values of V, there are two angles for which we observe a transverse speed of c, and for all the angles in between the transverse velocity will be larger than c.

Now let's take a look at some of the data, calculate the apparent speeds we're seeing and finding what actual speeds could account for them.

3.3 Looking at data

We will analyze data from two bodies, the cloud 3C345 [18], and the cloud 3C273 [19].

Below are the images from which we take our data.



By measuring the separation between clouds in all images, and assuming they have a recession velocity of 0.6c, we can easily find the transverse speed of these clouds. Unsurprisingly, most of these intervals indicate transverse speeds that are superluminal. Since these intervals have been measured by hand, there can be some error in our calculations.

Making the best measurements possible, we find transverse speeds that range from subluminal up to as fast as 7c. With this information in hand, we can try to find the minimum actual speed of the galaxy at which this effect can be observed, and we can do it in the same way as before. Figure #6 shows V_T vs θ for very high values of V.

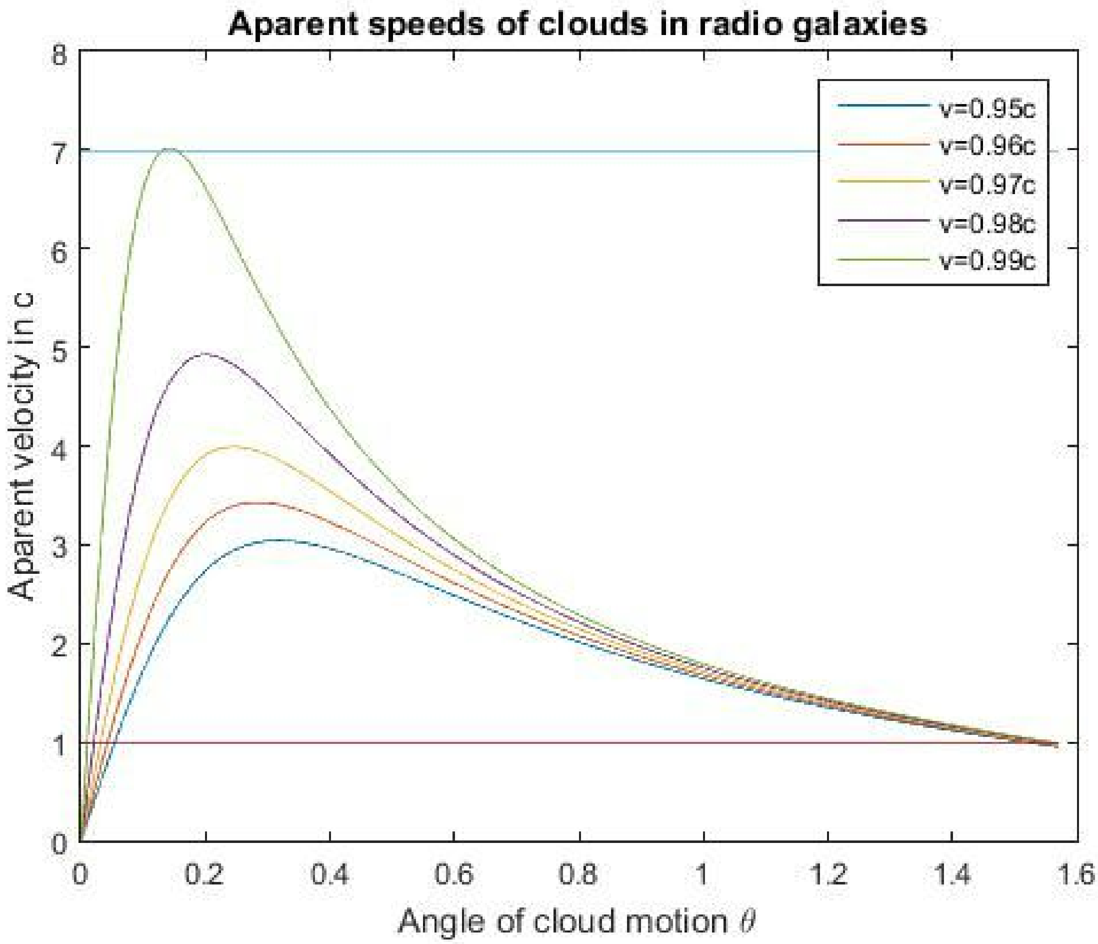


Figure #6

It can be seen very clearly that the cloud's real speed must be almost 0.99c before we can observe values of V_T as high as 7c. We can also see that for speeds as large as these, almost any value of θ will give a superluminal result.

3.4 Why does this superluminal effect arise?

When we get these results we know something must be moving at superluminal speed. We know it is not the cloud itself, because that is impossible. By looking at everything we've just gone over it is fairly easy to figure out that it is only the transverse component of the velocity that is greater than c.

It is the “shadow” of the motion, not the motion itself, which is superluminal. While at first that might seem counterintuitive (how can a component of a vector be larger that the vector itself?) there is a logical explanation. This is, of course, harder to explain conceptually than mathematically.

If one thinks about the fact that this cloud is going at speed comparable with c, in a direction somewhat towards earth, and also emitting photons which move at speed c in every reference frame, an idea can start to form. The idea is that this happens because the cloud is still relatively close to the first photon that was emitted when it emits the second photon. This causes the photons to be closer together in the direction towards earth, and so the interval of time between receiving the first and second photon becomes smaller and makes it appear as if it was moving faster transversely than it truly is.

4. Conclusion

This report has carried out a study of two types of superluminal motion, one that is truly so and the other only apparently so. Tachyons are particles that truly travel at speeds greater than that of light and whose existence in not theoretically forbidden, but they have never been observed. We showed how the Reinterpretation Principle could be used to interpret the interactions of tachyons with ordinary sub-light speed particles (bradyons) without the embarrassments of negative energy or backward travel in time. However there are other paradoxes that can be constructed with tachyons, such as Yoshikawa’s paradox, whose resolution poses difficulties and that continue to be debated by physicists today.

The second superluminal motion examined is the apparently faster than light motion of distant radio galaxies and gas clouds in the sky. This turns out to be an illusion and has a perfectly rational explanation when one takes into account the fact that these objects are very far away from Earth (in fact, at cosmological distances) where the finiteness of the speed of light kicks in and causes time intervals to shrink in a way that gives rise to the illusion.

As mentioned in the introduction, these two effects are not the only two superluminal motions that have been studied by physicists. There are a variety of superluminal effects in material media that are being actively studied [21-23] and that might make a good topic for a future MQP.

Bibliography

[1] O. M. P Bilaniuk, V. K. Deshpande and E. C. G. Sudarshan, “Meta“ Relativity, Am. J. Phys. 30, 718–723 (1962).

[2] G. Feinberg, Possibility of Faster-than-Light Particles, Physics review 159, 1089 (1967)

[3] G. Feinberg, Particles that Go Faster-than-Light, Scientific American 222, 68 (1970)

[4] R. G. Newton, Particles that Travel Faster-than-Light, Science 167, 1569 (1970)

[5] R. G. Newton, Causality Effects of Particles that Travel Faster than Light, Physics Review 162, 1274 (1967)

[6] L. Parker, Faster-than-Light Inertial Frames and Tachyons, Physics Review 188, 2287 (1969)

[7] M. M. Broido and J. G. Taylor, Does Lorentz-Invariant Imply Causality?, Physics Review 174, 1606 (1968)

[8] T. Alvager and M. N. Kreisler, Quest for Faster-than-Light Particles, Physics Review 171, 1357 (1968)

[9] M. B Davis, T. Alvager and M. N. Kreisler, Quest for Faster-than-Light Particles, Physics Review 183, 1132 (1969)

[10] M. Baltay, G. Feinberg, N. Yeh and R. Linsker, Search for Uncharged Faster-than-Light Particles, U.S. Atomic Energy Commission Report NYO-1932 (2)-148 (1969)

[11] M. Baltay, G. Feinberg, N. Yeh and R. Linsker, Search for Unchanged Faster-than-Light Particles, Physics Review D 1, 759 (1969)

[12] J. R. Gott, Time Travel in Einstein’s Universe, Houghton Mifflin Harcourt (2002)

[13] R.C.TOLMAN: The Theory of Relativity of Motion (Berkeley, Cal., 1917), p.54.

[14] O. M Bilaniuk, S. L Brown, B DeWitt, W. A Newcomb, M Sachs, E. C. G Sudarshan and S Yoshikawa, More about tachyons, Physics Today 22(12), 47 (1969).

[15] G. A Benford, D. L Book and W. A Newcomb, The Tachyonic Antitelephone, Physcal Rev. D, Third Series, Vol. 2, No. 2 (1970)

[16] O. M. P Bilaniuk and E. C. G. Sudarshan, Particles beyond the light barrier, Physics Today 22(5), 43 (1969).

[17] E. Recami, The Tolman "Antitelephone" Paradox: It's Solution by Tachyon Mechanics, Lett. Nuovo Cim. 44:587-593 (1985).

[18] Cohen, Active Galaxies and Quasistellar Objects, Superluminal Motion, http://ned.ipac.caltech.edu/level5/ESSAYS/Cohen/cohen.html

[19] Annual Review Astronomy and Astrophysics (1981) 19:373-410
https://ned.ipac.caltech.edu/level5/Kellermann/Kell6_2.html

[20] G. Ghisellini, Special relativity at action in the universe, Osservatorio Astronomico di Brera, v. Bianchi 46, I-23807
http://cds.cern.ch/record/387506/files/9905181.pdf

[21] L. J. Wang, Lijun Wang's experiment about supraluminal speed of light in a medium, Nature 406, 277 (2000)

[22] W. Withayachumnankul, A systemized view of superluminal wave propagation, Proceedings of the IEEE, Vol. 98, No. 10, pp. 1775-1786 (2010)

[23] http://www.ilp.physik.uni-essen.de/vonderLinde/Publikationen/APB96_gouy.pdf - Acceleration of femtosecond pulses to superluminal velocities by Gouy phase shift