Lecture Notes:
Is Interstellar Travel Possible?

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Introduction

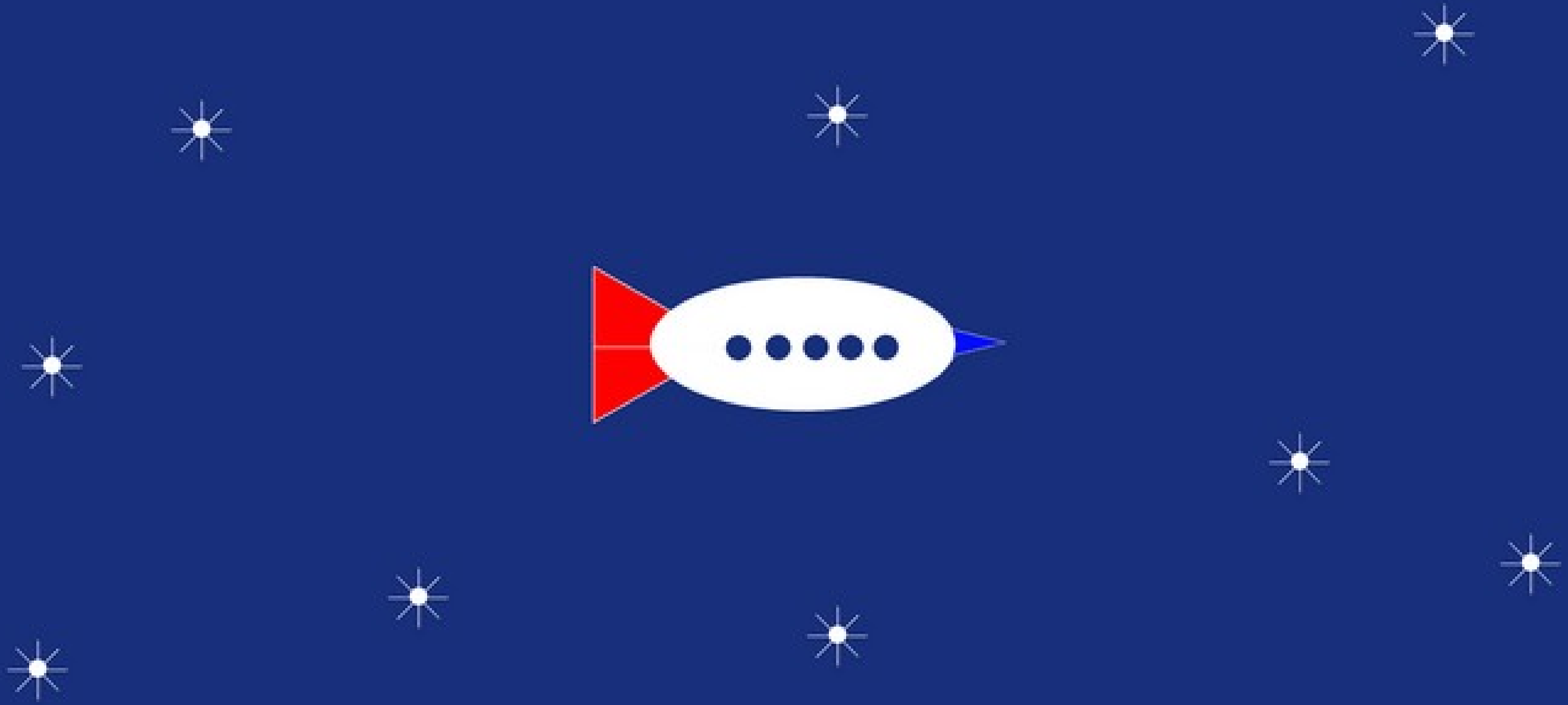
- This talk is entitled “Is Interstellar Travel Possible?”

- We ask the question because, these days, there seems to be a widespread assumption (one might even say an expectation) that humanity is destined in the future to go out among the stars and establish colonies on new worlds far away from our home on Earth. Some perhaps dream of galactic empires!

- But is it possible? Writers of science fiction seem to thinks so, and so do movie makers who, as a breed, seem to lean heavily towards the whole ‘empire’ thing.

- But is it really possible? I decided to do some research on the matter and found it to be an interesting exercise. I report my findings here, for you to ponder as you peer at the twinkling stars overhead – and dream of galactic empires.

The Challenge



Boldly going and exploring new worlds?

The Challenge

- This is our space ship which, in this talk, we will send on imaginary journeys.

- To those of you who think this space ship lacks style, let me point out two important facts

1. It is not necessary for a space ship to be sleek in a vacuum.
2. The ship is a British design – what could go wrong?

- So this is our challenge: could we ever realise a space ship cruising the space between the stars – boldly going and exploring new worlds etc.

To Infinity and Beyond….

Sun

2500 ly *

Deneb

Travelling at the *speed of light* a space ship would take 2,500 years to reach Deneb!

Game over?

No, let’s think about relativity theory.

* 1 ly = 9.46 x 10^{12} (9.46 trillion) km

To Infinity and Beyond….

- Let’s start with an imaginary journey – from the Sun to the star Deneb, which Wikipedia says is about 2,500 light years away.

- It might help to keep in mind that one light year is 9.46 trillion km.

- Einstein’s relativity theory says that nothing can travel faster than light, which is approximately 300,000 km/s. So let’s assume our space ship can travel that fast.

- The time it takes to complete the journey is, of course, 2,500 years!

- Would anybody in their right mind consider a journey that lasts longer than a civilisation? I doubt it!

- So is this game over?

- No, not really. We have been overly simplistic in our calculation. We need to understand Einstein’s theory a little better.

Relativity Theory

1. Nothing can travel faster than the speed of light (3 x 10^5 km/s).

2. Lorentz factor: $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ $\gamma \geq 1$

3. Moving objects contract: $L_{moving} = L_{static} / \gamma$

Lorentz contraction

4. Moving clocks run slow: $T_{moving} = T_{static} / \gamma$

Time dilation

Relativity Theory

1. As I have mentioned already, no object can travel faster than light. Note that light speed is usually given the symbol c in physics books, so I will follow that convention here.

2. Important effects that arise in relativity are governed by the so-called Lorentz factor, γ, which is a function of the speed of our space ship, v, and the speed of light, c, as shown here. γ can never be less than 1, a value it has when v is zero. But when v gets close to c, γ rapidly approaches infinity! We will see the significance of this in what follows.

3. There is a phenomenon called the Lorentz contraction, which says that the measured length of something when it is moving, is less than when it is when stationary. We may characterise this by the statement: moving objects contract in the direction of motion. The equation that describes this is shown on slide 7.

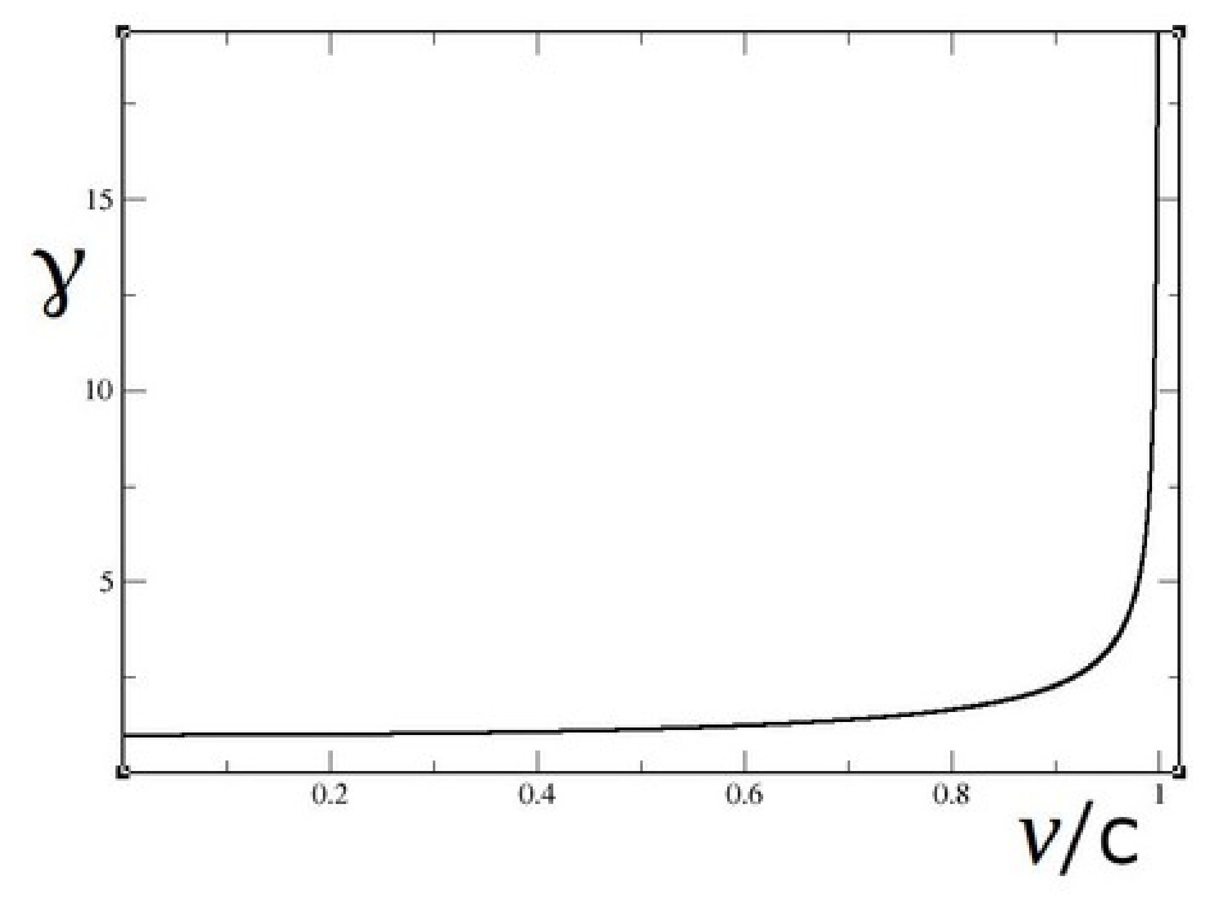
Relativity Theory

- Fourthly, there is another phenomenon called time dilation, which says that a given time interval, measured by a moving clock, is less than the corresponding time interval, measured by a stationary clock. We characterise this by the statement: moving clocks run slow. The equation describing this is shown on slide 7.

- Note how both effects have similar equations. They both depend on the parameter γ. When the speed is small these effects are negligible, but when it is near to light speed the effects are major.

- Lorentz contraction and time dilation defy common sense, but they are proven scientific facts.

The Lorentz Factor



The Lorentz Factor

- Slide 10 shows a plot of the Lorentz factor γ versus the speed v (expressed as a fraction of the speed of light).

- Notice that when v is small, γ holds close to the value of 1. This means that the effects of relativity are negligible and everything appears normal to our experience.

- This holds good until v is about 0.5 x c (or v~150,000 km/s in normal units), then the relativistic effects start to become noticeable.

- Not until the v gets to 0.866 x c (or v~260,000 km/s) does γ reach the value of 2, when significant effects are obvious.

- Once v gets beyond 0.9 x c (or v~270,000 km/s), γ quickly becomes very large and tends to infinity as it approaches c. The relativistic effects by this stage are profound.

To Infinity and Beyond….Again

For a space ship travelling at a speed v=99.999999% c, it turns out that the journey time experienced on-board is 129 days, which is a very reasonable time for such a journey. Such results imply that interstellar space travel is quite possible.

But how does relativity theory arrive at this result?

To Infinity and Beyond….Again

- Armed with our mastery of relativity, we re-examine the journey from the Sun to Deneb.

- Since we cannot actually travel at the speed of light, suppose we travel at 99.999,999% of light speed instead.

- Now, according to a clock that is stationary in our solar system, the time the space ship will take to get to Deneb is 2,500 years and 13 minutes. Not much change there!

- However, what we actually need to know is the time as measured on board the space ship. For that we need the time dilation equation and the value of γ, which turns out to be 7071 for the speed we have chosen.

To Infinity and Beyond….Again

- Using the time dilation formula gives 0.3536 years, or 129 days! That is about the time it took to get from England to India on a fast clipper in the days of the Raj. It is also about 1/7th of the record time spent in space aboard the ISS.

- The same result is obtained if we use the Lorentz contraction equation. Aboard our space ship the measured Sun-Deneb distance is contracted to 0.3536 light years, which at our chosen speed, will be travelled in 129 days.

- So, on this basis, it seems credible that we can actually travel to the stars!

Warp Speed

Relativity forbids speeds greater than c, so we can define speed as a fraction of c e.g. v=0.99999999c (often to many decimal places). This is not intuitively helpful to work with. So we use instead the warp speed ω, which we formally define as

$$\omega = \gamma v \quad \text{or} \quad \omega = \frac{v}{\sqrt{1 - v^2/c^2}}$$

For which the inverse is:

$$v = \frac{\omega}{\sqrt{1 + \omega^2/c^2}}$$

Warp Speed

- Now that interstellar travel seems possible, allow me to introduce what I think is a meaningful definition of warp speed.

- We have seen that the value of γ changes hugely when the speed is close to the speed of light. It follows that the effects of relativity are also greatest at this extreme. To give us fine control over the effects, we find we must specify many places of decimal, for example v=0.99,999,999 x c, and so on. This is not only inconvenient but also, not intuitively helpful – we have no ‘feel’ for what this number means.

- But there is an alternative. Instead we could define a speed, ω, which is γ x v, as given on slide 15. If we adopt this, we will generally find ω to be easier to handle than v.

- While v never exceeds the speed c, ω will often be very much larger than c, so we are justified calling it the warp speed.

Warp Speed

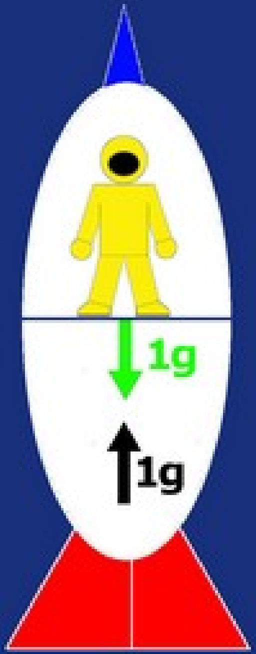
- Does the speed ω have a physical meaning? Yes – for our space ship it is the journey distance measured from the stationary starting point (e.g. our solar system), divided by the travel time as measured by a clock on board the space ship.

- This is intuitively sensible. If we know the stationary distance of travel and then specify the on-board time we desire for the journey, the warp speed will be our effective speed of travel.

- The actual speed v we need to travel at is given by the second equation, which is the inverse of the first. (But only the flight engineer needs to know this!)

- Note this equation can never return a value for v that exceeds the light speed c.

Artificial Gravity {ψ}



On board gravity is essential for long trips but how can it be created?

Einstein said acceleration and gravity are the same. (The Principle of Equivalence.) So an acceleration of 9.81 m $/s^2$ (1g) provides artificial gravity!

Flight plan: accelerate at 1g for first half of flight, then decelerate at -1g for the second half. Simple.

But how does this affect the journey time?

Artificial Gravity {ψ}

- Now we come to the idea of artificial gravity.

- We are probably all aware that spending a long time in zero gravity is detrimental to human health. So some means of re-creating gravity on board a space ship would be a good thing.

- Here we can turn to Einstein’s Principle of Equivalence, which states that gravity and acceleration are one and the same. It follows that if the space ship is accelerated at 9.81 m/s 2 (or 1g as it usually called) the astronauts on board would feel a downward force indistinguishable from Earth’s gravity.

- Our plan then, is to accelerate at 1g for the first half of the journey and then decelerate at minus 1g for the second half. Simple! - but remember to turn the ship around at the mid point, to stop everyone falling to the ceiling!

Artificial Gravity {ψ}

- Another issue that can be solved by this plan is how fast the space ship can safely be accelerated to warp speeds. Forget ‘jumping’ instantaneously to the required warp (as happens in science fiction) – that would merely squash everyone on board to a flat pancake! But accelerating at a steady 1g, would be perfect for a human body.

- Note however, that under this plan, the space ship is now undergoing a constant acceleration and not just cruising at a constant speed. There’s no serious drawback to this, but it does mean we need a new method to calculate the travel time.

Journey Time with ψ-Gravity

- I will present results for a journey from the Sun to mu-Cephei (better known as Herschel’s Garnet star), which is 6,000 light years away (according to Wikipedia).

- The flight calculations when using artificial gravity are complicated. The space ship travels with a varying speed and the relativistic effects change continuously.

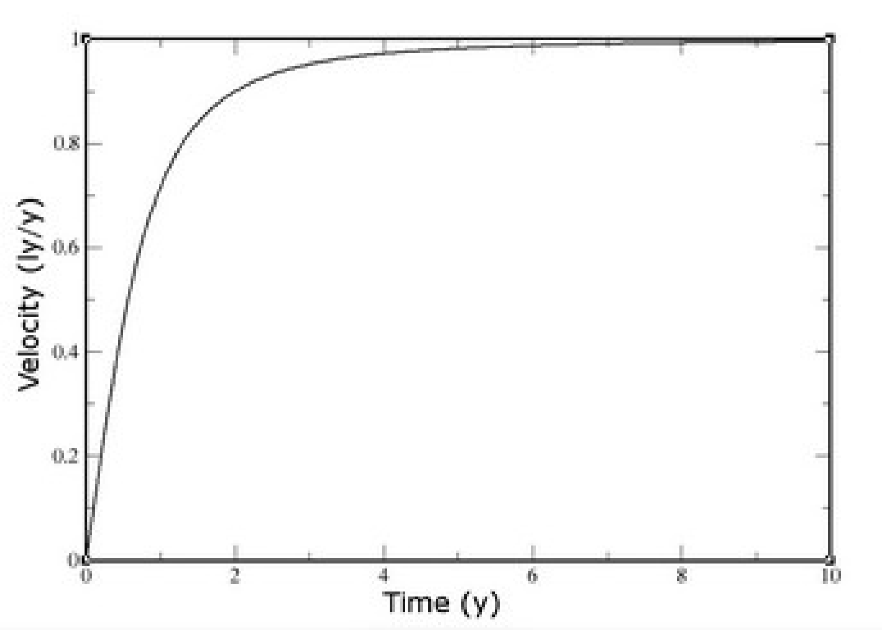
Briefly, these are the results:
1. The space ship reaches 98% of light speed in ~5 years.
2. The trip takes 6,001 years, 11 months in stationary solar system time.
3. The on-board time for the trip is 16.91 years.
4. The average warp speed is 355 times light speed.
5. The maximum warp speed is 3099 times light speed.

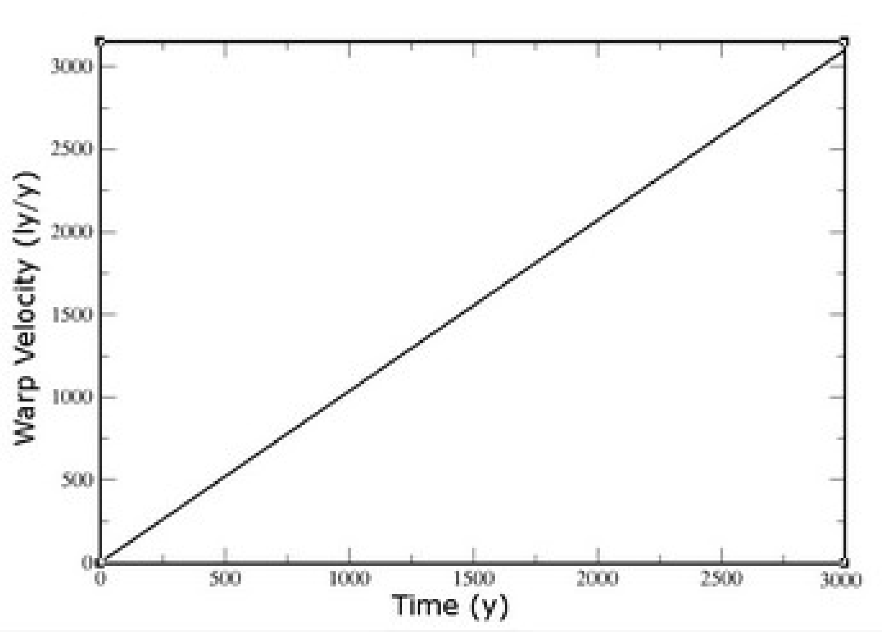
Journey Time with ψ-Gravity

- The results show that the requirement of a constant 1g acceleration has a big impact on journey time. However, we might have expected this, because we are no longer free to choose our speed of travel.

- A case can still be made for the feasibility of this journey. After all 6,000 light years is quite a challenge!

Real and Warp Velocities





Real and Warp Velocities

- Slide 23 shows how the real speed v and the warp speed ω change with stationary time (or ‘solar system’ time) or during a journey that incorporates artificial gravity. The speeds are shown in light years per year and the time is in years.

- The left hand plot shows the real speed v plotted against the time. We see that the speed increases linearly during the first year, but thereafter the plot bends over to the right as the observed acceleration begins to slow down.

- In five years we get to about 98% of light speed, but however long the journey, the speed of light will never be attained.

Real and Warp Velocities

- Beyond about 10 years there is hardly any observed acceleration at all, but despite all appearances, huge changes are happening to space and time as perceived aboard the space ship.

- The right hand diagram shows how the warp speed ω changes with the stationary time. It increases linearly for as long as the ship is being accelerated at the 1g required by the on board gravity.

- The simple relationship between the warp speed and the stationary time turns out to be key in relating observations made on board the space ship to those made from the solar system and vice versa.

Example Journey Times

Distance (ly)	Journey Time (y)	Avg. Warp Speed (c)
10	4.85	2.06
100	9.02	11.09
1000	13.44	74.40
10,000	17.90	558.6
100,000	22.36	4,472
1,000,000	26.82	37,286

Example Journey Times

- In this table we see some interstellar journeys and their corresponding on-board travel times.

- All these journeys are designed to make life on board the space ship optimal for human beings. There are no major physical stresses on the human frame, though psychological stresses are another matter!

- A journey of 10 light years takes 4.85 years. The average warp speed is therefore 2.06 x c. By today's standard, this would be a challenging journey for any astronaut, but impossible? I suspect not.

Example Journey Times

- At the other end of the scale, a journey of one million light years takes 26.82 years, at an average warp speed of 37,286 x c. This would be an incredible undertaking and a guaranteed one-way trip, but arguably not impossible.

- What is surprising is the relative journey time for a trip of ten light years against that for a trip of one million light years. The distance ratio is 100,000, but the time ratio is only 5.4! (Mathematically, the journey time scales with the logarithm of the distance.)

Pause: What does all this mean?

- Let’s pause here to reflect for a moment about what all this means. Here are some things to think about.

- Firstly, human beings might well be able to colonise the galaxy, for good or ill. Whatever the impact on the galaxy, it cannot be denied it would be an astonishing achievement.

- Secondly, there are a number of things we might casually imagine will come to pass, but in fact may be practical impossibilities. For example:

  - Return to Earth? As we have seen, the departure from Earth to a new world thousands of light years away can be accomplished in relatively few years, but by then the Earth will be thousands of years older and its civilisation possibly defunct and not worth returning to.

  - Emergency help in case of a catastrophe? This is obviously not practical – the inherent time delay renders it meaningless.

Pause: What does all this mean?

- Two-way communication between colonies? Any form of communication is limited by the speed of light. Useful dialogue may not be possible - who would wait years for an answer to a question? However, direct broadcasts would get through eventually. Party political broadcasts anyone?

- Trade between colonies? Once the customers get beyond a few light years, trade seems unlikely. Place your order and then what? Wait a few decades for the goods to arrive? Sending stuff in anticipation of need is possible, and the money could flow the other way on a similar basis but managing the flow, quantity and nature of the goods is problematic. These things need effective dialogue.

- Galactic empires? Good news! – empires are not possible. Rapid communication and response is essential to maintain an empire and, as we have seen, this is impractical. The bad news is that space piracy is feasible. Invading a colony, stealing resources and moving on, may in fact be the only viable form of interstellar commerce!

The Energy Problem

$$E = mc^2$$

Einstein’s equation

The kinetic energy of a space ship is given by:

$$K = (\gamma - 1) mc^2$$

m is the
rest mass

The amount of energy required for interstellar space flight
Is enormous. Where can this energy be found?

The Energy Problem

- Energy demand for relativistic space flight can be understood in terms of kinetic energy.

- Kinetic energy is the energy possessed by a speeding object. It is the energy of mass in motion, as revealed by its power to do damage!

- What we require is a source of energy (i.e. fuel), which we can convert via some sort of engine into the kinetic energy of our space ship. Just as rocket fuel provides the kinetic energy of a rocket.

- In anticipation of what the source of this energy is to be, we start with the most famous equation in physics: $E=mc^2$, Einstein’s mass-energy equation.

- This tells us is that mass and energy are equivalent and that a little mass can supply an enormous amount of energy. Since we will need a colossal amount of energy it’s best to discuss energy entirely in terms of mass.

The Energy Problem

- To get our space ship of mass m up to a speed v requires an amount of energy given by the equation on slide 31. Note the mc^2 term and the familiar γ parameter which, we recall, can be a huge number when close to light speed.

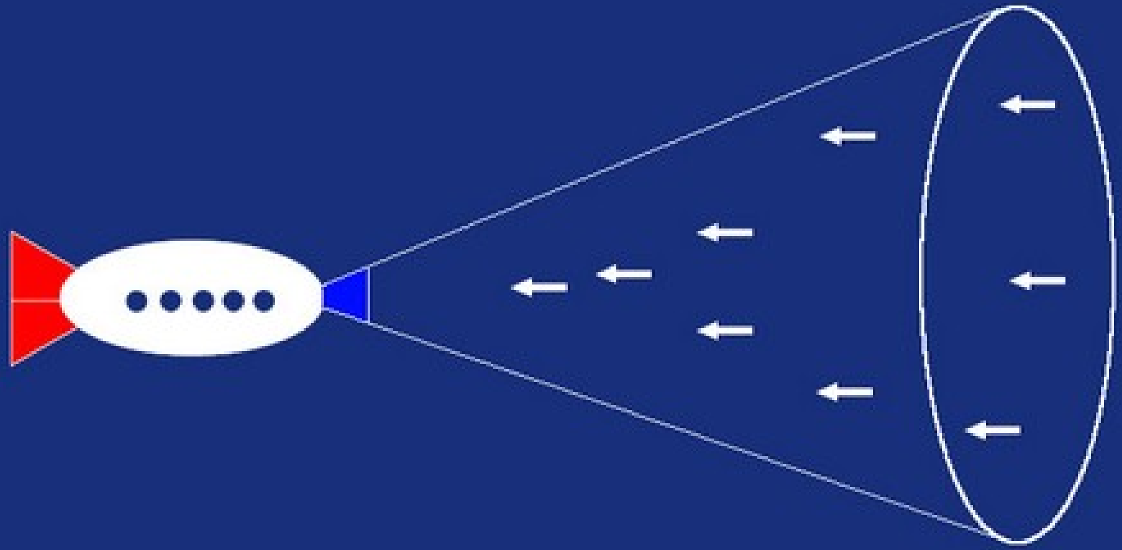
- As an example, this equation tells us that the kinetic energy of a space ship travelling at a warp speed of 1000 x c is equivalent to 999 times the mass of the ship! So if this mass of fuel can be converted purely into kinetic energy we will be able to reach the required warp speed. But where can such an enormous amount of energy be obtained?

- Note also that this energy is required just to propel the space ship alone. Nothing has been said about the mass of the fuel. Getting the on-board fuel up to speed also takes energy, which raises the question of how much extra energy this requires.

- We will bypass this issue in what follows by taking a different approach to sourcing the fuel.

The Interstellar Medium

Space is considered a vacuum, but it has an average of one million hydrogen atoms per cubic metre. So...



Construct a ‘sweeper’ to gather hydrogen fuel in flight and convert into energy by *mass annihilation* (using $E=mc^2$).

The Interstellar Medium

- To find the energy to propel our space ship we look to the interstellar medium.

- There are (on average) one million atoms of hydrogen per cubic metre of space and we intend to harvest this as our fuel.

- For this purpose we propose some sort of sweeper fronting the space ship to gather the hydrogen as the ship moves, rather as a jet engine gathers oxygen in flight.

- The sweeper will likely be electromagnetic in form, since one constructed of solid material will be prohibitively massive and vulnerable to damage.

- We speculate that the gathered hydrogen can be converted completely into pure energy by a process of mass annihilation. The liberated energy can then, by means of a rocket engine of some kind, be used to propel the space ship.

- However, there is no known physical process or associated engineering that can facilitate this at present. We are simply hoping it can be done!

The Sweeper Size

The diameter, B, of the sweeper can be calculated if we know the mass of the space ship (m), the density of the interstellar hydrogen (ρ), the acceleration for the artificial gravity (g), and the fraction of hydrogen that actually generates thrust (α).

$$B = \frac{2}{c}\sqrt{\frac{mg}{\alpha\pi\rho}}$$

For a space ship of 1000 metric tons (10^6 kg) B = 579 km!
This is feasible if the sweeper is electromagnetic.

The Sweeper Size

A hydrogen sweeper is not without its problems however, some of which are major. Here are a few.

1. The density of interstellar hydrogen is not uniform. There may be a deficiency in supply, or even an excess, but both will have to be managed somehow. A possible solution is to make the sweeper adjustable in size.
2. The interstellar medium is not hydrogen alone. In particular dust, granular matter and other solid objects will be serious impact hazards. (And do not mention asteroids!). I have no solutions for this problem.
3. The space ship travels at near light speed. Collisions with atomic matter will be no different from the collisions in a particle accelerator. The atomic integrity of the ship is therefore in jeopardy. A possible solution is to ensure the sweeper is strong enough to direct atomic matter through the ship’s engine where it can be utilised or expelled without making contact with the ship’s material structure.
4. The interstellar matter interacting with the space ship and the sweeper gives rise to a drag force opposing the forward motion. This turns out to be a critical issue we should explore in more detail.

The Drag Force

Interstellar hydrogen has a very low density (1.66 x 10^{-21} kg/m^3). Is this sufficient to cause problems? – absolutely! Its momentum as it collides with the space ship is sufficient to generate a major drag force resisting forward motion.

$$f_{drag} = \frac{\pi}{4} \beta \rho B^2 \gamma v^2$$

The drag force increases with speed, eventually it nullifies the propulsive force entirely and cancels the acceleration – the space ship has a fixed maximum speed!

The Drag Force

- Even though the density of hydrogen in space is low, the speed of the space ship is so great it encounters a huge quantity of it every second. The difference in momentum between the space ship and the intercepted hydrogen generates an enormous drag force that will resist the ship's forward motion.

- The formula for the drag force is shown on slide 38. ρ is the density of the inter-stellar gas. B^2 defines the area of drag for the ship. (We may take this to be the diameter of the sweeper.) The term γ meanwhile, will be extremely large. The term v^2 will approximate to c^2 in practice, providing another huge, decelerating factor.

- The parameter β is what might be called a streamlining factor with a value between 0 and 1. It allows for the possibility that some change in the geometry of the space ship may lower the drag force. But if β defaults to 1, the full drag force will act.

- The existence of the drag force puts a limit on the speed of the space ship, so we may never get to the warp speeds that make interstellar travel viable. Also, a limiting speed means there will be no acceleration, which means no artificial gravity either.

The Space Ship Equation of Motion

$$m\gamma^3\dot{v}=\frac{\pi}{4}\rho B^2\left(\alpha c^2-\beta\gamma v^2\right)$$

So if $\dot{v}=0$: $\left(\alpha c^2-\beta\gamma v^2\right)=0$

Hence: $$\frac{v^2/c^2}{\sqrt{1-v^2/c^2}}=\frac{\alpha}{\beta}$$

If $\begin{matrix}\alpha=1\\ \beta=1\end{matrix}$: $\begin{matrix}v_{max}=0.786\times c\\ \omega_{max}=1.272\times c\end{matrix}$

The Space Ship Equation of Motion

- Here is the equation of motion for the ship. Ignore the details, the important point is that it proves that there is indeed a limiting speed to the space ship.

- The middle equation is key. On the left hand side is gathered all the speed terms and on the right are the parameters α and β in the form of a ratio.

- α, we know, is the efficiency of the energy production process. β is the streamlining factor. The bigger this ratio, the bigger the maximum speed. So we need a big α and a small β for the best outcome.

- Alas, neither is likely. It is more likely that α will be small and β large (i.e. low propulsion efficiency and high drag). So our prospects are not good!

- Taking the α–β ratio to be 1 (representing a ‘middling’ value), we find that the maximum speed is 0.786 c, which means the maximum warp speed is 1.272 c.

This is not good enough!

Conclusions (so far)

- Theory suggests that travel between stars in the span of one human life may be possible, though in many cases the journey can be one way only.
- Energy generation is required on an unprecedented scale implying complete mass annihilation as the source.
- Interstellar hydrogen is a potential fuel source, but its availability is variable.
- Collision with interstellar matter threatens the structural integrity of the space ship.
- The drag force arising from the interstellar matter will render the idea impractical if it cannot be overcome.
- The technological challenges are inevitably extremely demanding!

Parting thought:

No interstellar journey is worth undertaking. The distances are so large and journey times so long the space ship will inevitably be overtaken by a later one propelled by more advanced engineering.

Smith’s Paradox

The End