Momentum Exchange Banks

Propellantless Propulsion

Galen Matson

Momentum Exchange Banks (MEBs) are proposed orbital megastructures that function as inertial relays. They capture inbound spacecraft using tethers thousands of kilometers long. These MEBs absorb kinetic energy as rotational inertia in massive flywheels. The energy is transferred by reeling in and releasing outbound ships at a high velocity. Conserving momentum allows spacecraft to travel propellantlessly between planets with Momentum Exchange Banks.

These enormous machines can convert between kinetic and electrical energy on a massive scale. Much of the launch energy can be gained from orbital stationkeeping measures such as light sails and electrodynamic tethers making space travel between these momentum banks as close to a free launch as physics allows.

With reasonable advancements in materials technology, extremely high velocities and payload masses are achievable. MEBs at strategic locations across the solar system can inexpensively launch spacecraft and cargo between every planet, moon, Lagrange point, or space station. This fundamentally alters the economics of space travel, facilitating the colonization and industrialization of space and even interstellar travel.

Introduction

To travel from one planet to another a rocket must carry enough propellant to accelerate to a high velocity and slow down at its destination. Economic (slow) space travel takes years. Humans get bored in minutes. The ship has to be fast and that means more propellant. More propellant adds more weight requiring more propellant. The ship must also carry enough propellant to stop at its destination and most of the energy spent accelerating is wasted slowing down. The costs mount geometrically. This is the tyranny of the rocket equation.

With tether launches from Momentum Exchange Banks, a majority of the ship's energy is conserved within the Momentum Exchange Network so most of the ship can be allocated to payload and passengers and it will reach much higher velocities.

In this paper I demonstrate the feasibility of momentum exchange between orbits, planets, Lagrange points, and stars. No new physics is required; this is super basic stuff scaled to magnificent proportions, limited by materials and manufacturing.

I first describe the basic physics of launch and capture and characterize the energies involved. Then I detail the mechanics of the critical subsystems, their performance requirements, and capabilities. After demonstrating the physics and mechanics I scale the system to show how coordinated teams of Momentum Exchange Banks can send ships anywhere in the solar system and beyond.

This is a paper on physics and engineering but it is intended for a general audience. It is still in progress so if something is wrong, hard to understand, or said poorly please tell me.

Momentum Exchange Network

A momentum exchange bank functions like a deep water port and an airport all at once. They can send large payloads on slower, economical trajectories and small payloads quickly across the solar system. Connecting a colony to the network of momentum banks across the solar system brings colonists and resources. Once MEBs are widely distributed across colonized space they facilitate trade that would be otherwise uneconomical.

The composition of our solar system is stratified such that inner planets are rocky with abundant heavy metals but deficient in light gasses while outer planets are mostly made of light gasses and deficient in heavy elements. All elements are needed in vast quantities for a functioning stellar economy.

The gravity at the cloud tops of Saturn, Uranus, and Neptune are similar to gravity at Earth's surface. Gas refined from their atmospheres can provide hydrogen for propellant and helium-3 and deuterium fuel for fusion reactors. The ice moons are rich in volatiles like ammonia and methane which are vital for fertilizers and polymers. The inner system, including the rocky moons and asteroids, have concentrated metals essential for rigid structures and pressure vessels like habitats, ships, and space stations.

A vibrant interplanetary economy creates a vastly different future than one so limited by transport costs that colonies live near subsistence, dependent on massive subsidization by their homeworld. With economical transport they can specialize, prosper, and gainfully contribute to an interplanetary economy.

A Momentum Exchange Network facilitates rapid travel throughout the solar system, potentially reducing trips from Earth to Mars from months to weeks and trips from Earth to Jupiter from years to months. Launches needn't be timed to perfectly coincide with planetary alignments; ships can take orbit crossing trajectories to save time. Relay networks of MEBs could even accelerate ships to interstellar velocities.

Comparison to Rockets

An efficient transfer from Earth to Mars requires a total change in velocity of 5.7 kilometers per second for speeding up and slowing down. If we wanted to send a 10 thousand ton ship there, how much fuel would we need?

The rocket equation is:

$$\Delta V = I_{sp} \cdot g \cdot ln\left(\frac{m_0}{m_p}\right)$$

Where:

The change in velocity is called delta V (Δv) = 5.7 km/s = **5700 m/s**

I_{sp} is 'specific impulse'. It means, if you put your foot on the gas and keep the acceleration steady, how long you would accelerate before emptying your tank. So if the fuel tank is the same size and the acceleration is the same, a more efficient engine would accelerate for longer. The best chemical rocket engines currently have an Isp of **450 seconds** for hydrogen/liquid oxygen (hydrolox) engines.

The acceleration of our ship will be 1 Earth gravity (g) = **9.80665 m/s^2**.

The natural logarithm (**e**) is the rate of change in the mass of the ship. In this case the mass decreases as the fuel in the ship is burned so the ship gets lighter and the acceleration increases. We'll use the symbol (e) because that's on your calculator and I know you're checking my math.

The payload mass (m_p) = **10,000 tons**

The starting mass is (**m_0**), which will be the maximum size of the ship, including payload and fuel before departure.

We'd like to know how much fuel we need to get to Mars so we solve for the ship's starting mass to payload ratio:

$$\frac{m_0}{m_p} = e^{\frac{\Delta V}{I_{sp} \cdot g}} = e^{\frac{5700}{450 \times 9.80665}} \approx e^{1.29164} \approx 3.638$$

This gives us the ratio of full mass to final mass. The final mass is 10,000 tons * 3.638 = 36,380 tons full.

Subtracting the payload: 36,380 - 10,000 = 26,380 tons of propellant

Dividing the fuel mass by the total mass: 26380 / 36380 ≈ .725 * 100 = 72.5%

Python: Rockety.ipynb

To get a 10 thousand ton ship from Earth orbit to Mars orbit would require 26 thousand tons of fuel, 72 percent of its starting mass and take 6 months. A lot of the payload mass is engines and fuel tanks, even when empty they are still heavy so the useful payload would be a lot less than 10 kilotons. The momentum bank can increase the useful payload mass while reducing the travel time.

Assumptions

This paper assumes an infrastructure project like the Momentum Exchange Network would happen decades in the future, in a period of colonization and industrialization of space. Momentum Exchange Banks require megatons of ballast mass. A project of this scale presumes economical access to the products of space based industry like structural metal and sources of inexpensive ballast such as lunar regolith.

This also assumes advancements in materials science, specifically around the mass production of atomically flawless carbon nanostructures, particularly monolayers very strong under tension and lattices very strong in compression.

Flawless monolayers

Graphene is a hexagonal lattice made of pure carbon which has the highest tensile strength, melting point, and electrical conductivity of any known material. Carbon is plentiful but graphene's perfect hexagonal arrangement of sp^2 carbon bonds is difficult to produce at scale with current technology.

The production of graphene has accelerated significantly; going from microscopic to meters in the last decade. I assume this will continue or accelerate until this metamaterial reshapes infrastructure on Earth and makes infrastructure in space possible.

Hexagonal Boron Nitride monolayers are similar in strength to graphene. Graphene is an excellent conductor but, importantly, hexagonal boron nitride is a powerful electrical insulator.

Graphene and boron nitride's exotic tensile strength and excellent electrical properties are indispensable to the designs and conclusions in this paper.

Carbon Nanolattices

Nanolattices are rigid 3 dimensional structures made of ordered, repeating atomic bonds. The tension of the bonds creates a high compressive strength.

In a recent breakthrough, researchers used machine learning to model different shapes of carbon lattice to discover a rigid lattice structure stronger than steel and light as styrofoam.

While traditional metals can meet the compressive strength requirements for the structures proposed here; their power, durability, and utility are vastly magnified with lighter and stronger materials.

Superconducting Semiconductors

At the end of this proposal is an orbital scale linear accelerator which relies on superconducting magnetic energy storage and superconducting field windings to contactlessly boost and brake tethers electromagnetically, similarly to a MagLev train. The energies involved require superconducting switches with rapid transitions.

This has been a major limitation, particularly in the field of nuclear fusion, however recent breakthroughs make this seem like a realistic technology now. Without this technology the achievable velocities are more than halved.

Momentum Exchange Mechanics

We'll establish the working physics of MEBs by optimizing for a given exchange of energy: accelerating a 10 kiloton mass by 10 kilometers per second. Furthermore, the reciprocal acceleration on the MEB should not exceed 1 meter per second.

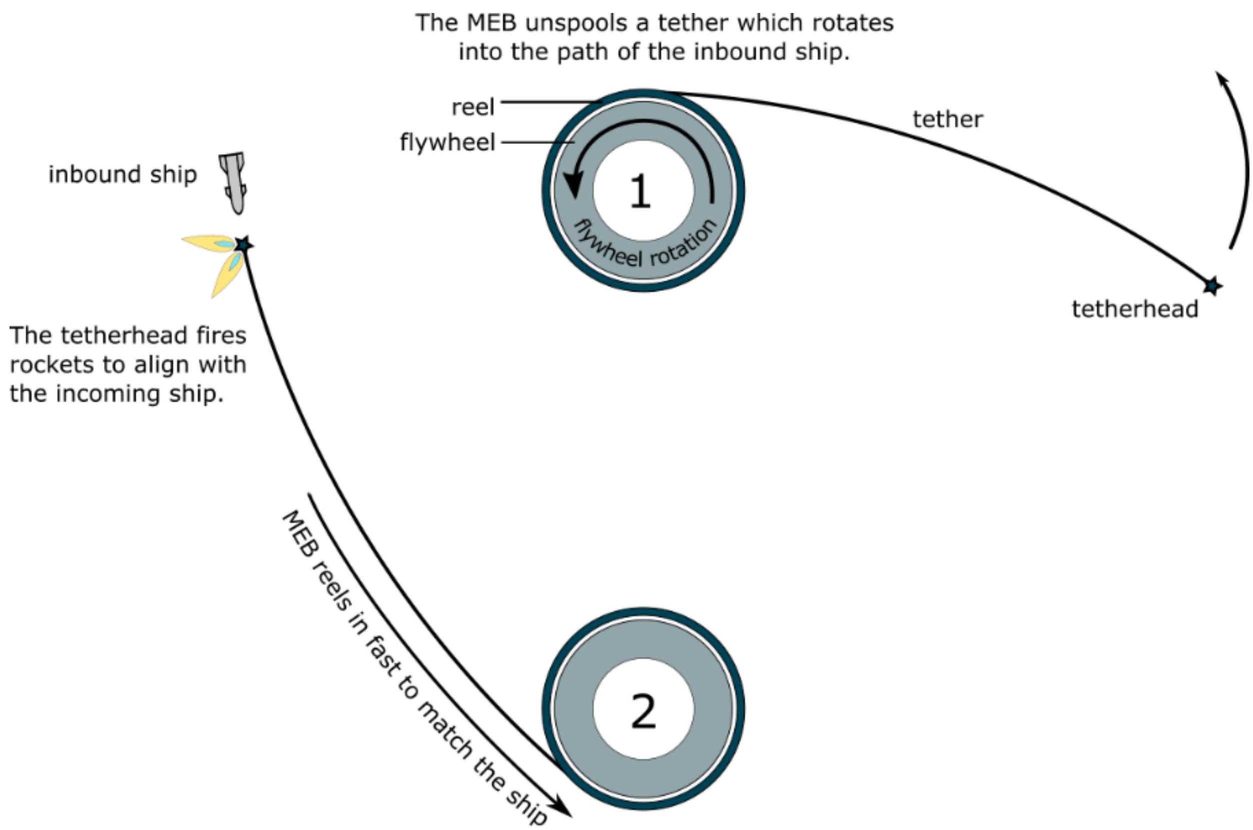
These values are chosen because 10 kilotons would be a comfortably sized ship for interplanetary travel (this is 20 times the mass of the International Space Station). Accelerating the ship by 10 kilometers per second is a good change in velocity that will get you just about anywhere in the solar system. And decelerating the momentum bank by 1 meter per second is slight enough that successive launches won't cause it to fall out of orbit before the velocity can be regained.

Force Application

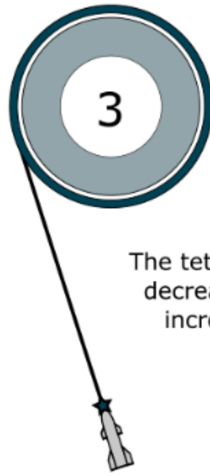
When launching, force is applied from one mechanical system to the next ultimately transferring momentum from the flywheel to the ship.

- Flywheel: The flywheel spins at a fairly constant rate and provides the anchoring mass for the rest of the system to act on.
- Reel: The reel spins around the flywheel to position the tether at a tangent to the payload and maintains this alignment while the launch force is applied.
- Windlass: The windlass affixed to the reel houses rollers and accelerators and spools and unspools the tether.
- Rollers: Rollers clamp the tether and spin, mechanically accelerating the tether. They unspool the tether from the reel and gather it back in.
- Accelerators: The linear accelerators sandwich the tether with superconducting field coils and contactlessly accelerate the payload with a powerful traveling magnetic field.
- Tether: The tether transmits the applied force to the tetherhead.
- Tetherhead: The tetherhead is a maneuvering spacecraft with rockets, reaction control systems, anchor points (for other tetherheads to attach), and dozens of load spreading payload clamps.
- Payload: The payload is a ship or container that has suitable attachment points for latching by the tetherhead and its structure can handle the tensile strain of the acceleration rate negotiated with the MEB.

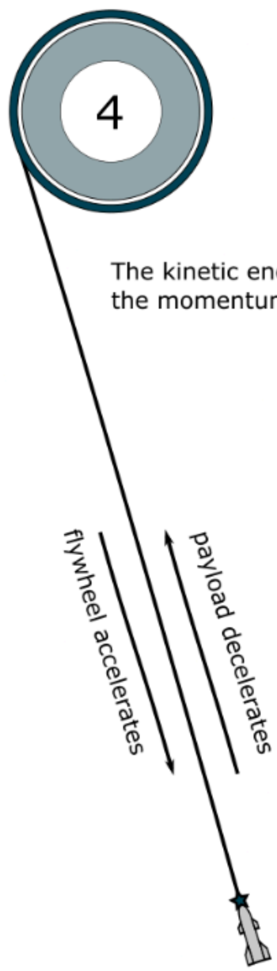
Here's a sequential depiction of the payload capture process. Functionality of the components is described in later sections. This is not to scale.



After latching the inbound ship the reel reverses direction, applying a braking force.



The tether unreels up to its full length, decreasing the deceleration force by increasing the deceleration time.



The kinetic energy of the ship is absorbed by the momentum bank.

The ship is released when the desired change in direction or velocity has been reached.

Payload Kinetic Energy

How much energy are we talking about? First let's calculate the total kinetic energy to accelerate 10 kilotons by 10 kilometers per second:

The mass of the ship (the payload) is 10 kilotons which is 10,000,000 kilograms: $m_{payload}$ = **$1 \cdot 10^7$ kg.**

The velocity of the ship is 10 km/s which is 10,000 meters per second: v = **$1 \cdot 10^4$ m/s**

You might recall from the gun range that the kinetic energy of a projectile rises linearly with mass but exponentially with velocity. Doubling the mass doubles the energy whereas doubling the speed quadruples the energy. This is the kinetic energy equation: $E = 1/2mv^2$

We'll find the ship's total kinetic energy (E) in Joules by multiplying its mass by 1/2 and squaring its velocity:

$$E = \frac{1}{2}m \cdot v^2 = (\frac{1}{2} \cdot 10^7 kg) \cdot (1 \cdot 10^4 m/s)^2 = (5 \cdot 10^6 kg) \cdot (1 \cdot 10^8 m/s)$$

$$E = 5 \cdot 10^{14} Joules = 500\ TJ$$

It takes **500 TeraJoules** to accelerate a 10 kiloton payload to 10 kilometers per second. This is a lot of energy, equivalent to 120 kilotons of TNT, similar to a low yield nuclear weapon or a banana at 30% of light speed. We'll see later how this kinetic energy compares to the stored energy in the momentum exchange bank.

Momentum Bank Mass

For momentum conservation, the same force applied to the payload is applied to the MEB. Its high mass counterbalances its change in velocity. Limiting the recoil to **1 m/s** we can calculate the minimum mass of the momentum bank:

$$m_{MEB} = \frac{m_{payload} \cdot \Delta v_{payload}}{\Delta v_{MEB}} = \frac{10^7\ kg \cdot 10^4\ m/s}{1\ m/s} = 10^{11} kg$$

The change in velocity of the momentum exchange bank must be low enough that it can launch many payloads without wandering out of its orbit. Limiting this to 1 meter per second while accelerating a 10 kiloton ship to 10 km/s requires a mass of **100**

megatons. Greater ballast mass increases the time the MEB has to balance itself with momentum exchanges and stationkeeping measures.

Flywheel

The core of the momentum bank is the massive flywheel. It resists changes in momentum when catching or launching payloads, and it stores energy as spin. The flywheel itself comprises 99% of the total mass of the momentum exchange bank. The power plant, reels, radiators, tethers, rollers, accelerators, magnetic bearings, control systems, and other vital parts will likely mass only hundreds of kilotons in combination compared to the megatons of ballast mass in the flywheel.

It should spin as fast as feasible to store the maximum amount of inertia. So it should itself be made of graphene or be a graphene reinforced composite structure. The geometry of the flywheel could be a cylinder of any shape but a tall cylinder would wobble and eventually tumble end over end. The most stable flywheel would be as thin and wide as practical to avoid precession. Therefore the flywheel should have a high width to thickness ratio.

The dimensions used in the following calculations will be a ring **4 kilometers in diameter** and **100 meters thick**. For simplified calculations the entire mass of the momentum bank will be modeled as a balanced hoop with the entire **100 megatons** of ballast distributed evenly around the outside.

Ballast Materials

To maximize economic value, momentum banks should be deployed widely across the solar system including every planet, moon, major asteroid, Lagrange point, and even solar orbits. Location in the solar system determines the availability and type of ballast materials which might drastically affect the cost. In the rocky inner system dirt, also known as regolith, is abundant and cheap while water is cheaper than dirt in the outer system.

Lunar Regolith

The first momentum banks will probably shuttle payloads between Earth and Lunar orbit. Lunar regolith is the obvious first choice for a bulk material to ballast the momentum bank. The moon’s accommodating gravity allows payloads to launch with mass drivers right off the surface and into space. The first momentum banks will likely be weighted with unprocessed Lunar regolith. We will briefly look at alternatives and their availability throughout the solar system.

Slag

Space stations and colonies on other worlds will require massive quantities of steel, aluminum, titanium, magnesium, and other metals processed into girders, trusses, pipes, plates, tanks, wires, habitats, and everything else to support the expansion of humanity into space.

Metal smelting from natural ores produces byproducts called slag which is primarily composed of silicon, calcium, and titanium oxides. This slag will have little other economic value except as radiation shielding or aggregate in construction making it a suitable bulk mass for momentum banks with potentially higher density and greater uniformity than unprocessed regolith.

Asteroid Regolith

Asteroids will be a convenient source of ballast mass, especially in space far from planets or moons. Only about 10 percent of main belt asteroids are minable metallic asteroids. The majority are C and D type carbonaceous asteroids. This includes the moons of Mars, Phobos and Deimos, which appear to be captured asteroids.

They are composed primarily of clays, silicates, and carbon compounds. Their powdered regolith would have a density similar to lunar regolith. Most sunward asteroids are agglomerated 'rubble piles' of dust and porous, low density carbon and silicon rocks with little economic value other than weighting megaton flywheels in momentum banks.

The asteroid belt, Kuiper belt, and Oort cloud are teaming with asteroids which can be a source of ballast mass. Besides the asteroid belts they tend to collect in the stable L4 and L5 Lagrange points. These are gravitational balance points in the orbits of massive planets. Venus, Earth, Jupiter, Saturn, Uranus, and Neptune all have these 'Trojan' asteroids at their Lagrange points.

Earth's L4 has multiple known asteroids including (614689) 2020 XL5, which is a carbonaceous C type asteroid approximately 1.18 km in diameter. While there is no official mass estimate, we can make a first order approximation by taking the density of similarly sized C type asteroids and modeling it as a sphere (it's probably not) and get a ballpark mass estimate with some big error bars:

Average C type asteroid density = 1700 kg/m^3

(614689) 2020 XL5 radius = 1.18 km / 2 = 590 m

Volume of a sphere = $\frac{4}{3}\pi r^3$

Volume of (614689) 2020 XL5 = $\frac{4}{3} \cdot \pi \cdot 590m^3$ = 860,289,543.47 m^3

Mass = density * volume

(614689) 2020 XL5's mass = 860,289,543.47 m^3 * 1700 kg/m^3 = 1,462,492,223,897 kg = **1.46 gigatons**

Python: (614689) 2020 XL5.ipynb

Well that's a heavy rock! We just need to pinch off 100 megatons for a momentum bank. Or, bag the whole asteroid and flatten it into a gigaton flywheel, put a central shaft through it and mount some habitat rings, now you've got a nice space station at Earth L4. There's rocks like this all over the place so, even in deep space, there is mass available for Momentum Exchange Banks or other uses.

Ices

The sun's heat creates a 'snow line' in the asteroid belt such that inward asteroids and moons tend to be devoid of volatiles, meaning easily evaporatable stuff like water, methane, carbon dioxide, and ammonia.

Asteroids and moons beyond the snow line have lots of volatile compounds, increasing in relative abundance the further away from the sun you get. Objects in the outer system are composed primarily of ices of frozen volatile compounds. Sputnik Planitia, the famous 🤍 of Pluto, is in fact a layer of frozen nitrogen. Nitrogen has such a low freezing point it only condenses beyond the orbit of Uranus.

The crust of every moon beyond Mars is ice, including the moons of Jupiter, Saturn, Uranus, and Neptune (with the possible exception of Titan which is a hydrocarbon slushie).

Most of the asteroids that far out are significantly composed of ice. Comets are icy asteroids with elliptical orbits that take them within the snow line where the sun boils away their volatiles creating the glowing comet tail. Although less dense than rocky materials, ice is dense and abundant enough to provide the ballast mass for momentum banks very far from the sun.

Liquids

Liquids, such as water or hydrocarbons are dense, self balancing under centrifugal force, and have a high heat capacity to sink a great deal of waste heat from a reactor or friction from momentum exchanges. With heat and pressure the water can be kept liquid.

Baffles inside the flywheel can turn it into a massive torque converter, applying dynamic resistance during momentum exchanges. If the geometry of the baffles can vary the resistance and deflection this presents a mechanical method for balancing and dynamically coupling the ballast mass in a relatively simple and low tech manner.

Liquids could introduce new instabilities or complexity due to sloshing, waves, or tides from gravitational perturbations. High viscosity liquids or slurries might mitigate some of these issues. These considerations are outside the scope of this paper so a dry ballast of lunar regolith will be assumed for the example momentum bank in the following sections.

Hoop thickness

The abundance of regolith, mine tailings, smelter slag, and ices all indicate that some suitable ballast mass is available almost anywhere in the solar system.

For modeling rotational inertia the shape of the flywheel is a hoop with all of the mass on the rim. Below is a table of ballast materials with their density, the total volume required for 100 megatons of mass, and how thick a hoop of that mass would be.

Material	Density (kg/m^3)	volume (m^3)	hoop thickness (m)
Lunar Regolith	1700	5.88E+07	46.81
asteroid regolith	1600	6.25E+07	49.74
lunar ilmenite slag	1800	5.56E+07	44.21
Water	1000	1.00E+08	79.58
Water Ice	917	1.09E+08	86.78
Methane Ice	470	2.13E+08	169.31
Ammonia Ice	817	1.22E+08	97.40
CO2 Ice	1562	6.40E+07	50.95
nitrogen ice	940	1.06E+08	84.66

For a flywheel 4 kilometers across and 100 meters wide, a hoop of evenly distributed lunar regolith would be less than 50 meters thick. Based on this we can safely use simple hoop stress calculations to determine the inertia and mechanical stress on the flywheel.

Rotational Inertia

How much energy is stored in a momentum bank? For simplified calculations we will assume that the entire mass of the MEB is the flywheel. The flywheel is 2 kilometers in radius, it is weighted with 100 megatons of lunar regolith. Its rim is made of graphene and we limit the centrifugal force to 50 percent of its breaking strength for an excellent safety margin.

The formula for rotational kinetic energy is $E = \frac{1}{2} I\omega^2$ where:

E is the energy in Joules

I is the Moment of Inertia

ω is the rotation rate in radians per second

To solve this we need two things first, the Moment of Inertia (*I*) and the rotation rate (ω). The rotation rate requires the Moment of Inertia, so let’s figure that out first.

Moment of Inertia

So much of the mass is on the rim that we can use the formula for a hollow cylinder to determine the Moment of Inertia: $I = MR^2$ where:

M is the MEB mass: 100 megatons = **10^{11} kg**

R is the radius = 2 km = **2000 m**

So the Moment of Inertia increases linearly with mass (M) and squarely with radius (R). Plugging our values in:

$$I = MR^2 = (10^{11} kg) \cdot (2000 m)^2 = (10^{11} kg) \cdot (4 \cdot 10^6 m^2) = 4 \cdot 10^{17} kgm^2$$

Python: Flywheel Inertia.ipynb

The Moment of Inertia is 400 quadrillion kgm^2. Which is 400,000,000,000,000,000 kilogram square meters. That's a really big number! For comparison: 30,860,000,000,000 kilometers is also a really big number.

Rotation Rate

With the Moment of Inertia we can figure out the rotation rate. If the flywheel is a thin hoop, we should first find out how fast it can safely spin before exceeding 50 percent of graphene's tensile strength.

The formula for calculating hoop stress, commonly used to figure the disintegration point of spinny things like tires is:

$$\sigma = \rho R^2 \omega^2$$

Where:

σ is the tensile strain in Pascals, which is a force in Newtons spread over an area in square meters (N/m^2). We're using 50 percent of graphene's tensile strength which is 130 GigaPascals / 2 = 65 GP = **$65 \cdot 10^9$ Pa**.

ρ is the density of the material in kilograms per cubic meter which is **1700 kg/m^3** for lunar regolith.

R is the radius in meters, 2 kilometers = **2000 m**

ω is the rotation rate in radians per second.

We want the rotation rate so we rearrange thusly:

$$\omega = \sqrt{\frac{\sigma}{\rho R^2}}$$

And slide in our shiny new values:

$$\omega = \sqrt{\frac{65 \cdot 10^9}{1700 \cdot (2000)^2}} = \sqrt{\frac{65 \cdot 10^9}{1700 \cdot 4{,}000{,}000}} = \sqrt{\frac{65 \cdot 10^9}{6.8 \cdot 10^9}} \approx \sqrt{9.56} \approx 3.09\, rad/s$$

Python: Flywheel Inertia.ipynb

The rotation rate is approximately **3.09 radians per second**, which is approximately 29.5 revolutions per minute. This results in a tangential velocity of 6.18 kilometers per second at the rim.

For context, an average dwarf hamster can easily maintain 30 RPMs on a 25cm hamster wheel. If we doubled the exercise wheel diameter to 50cm, only a motivated Syrian hamster could maintain 30 RPMs. However, the rotational energy scales according to $\frac{1}{2}I\omega^2$; this quadruples the kinetic energy in the wheel while only doubling the hamster force. This is clearly the way to optimize for kinetic energy of megascale interplanetary accelerators.

Later sections on Reels and Linear Accelerators show that a very high rotation rate for the flywheel itself may not be necessary or desirable. These calculations are meant to show that tremendous energy can be stored with a heavy spinny thing.

Kinetic Energy

We finally have everything we need to calculate the kinetic energy of the flywheel at the heart of this monstrous space contraption. Let's bring back that formula we started with. We've both forgotten it so I'll just cut and paste:

$$E = \frac{1}{2} I \omega^2$$

Right, energy is half the moment of inertia times the speed squared so let's whack our values in there:

I (moment of inertia) = $\mathbf{4 \cdot 10^{17}}$

ω (rotation rate in radians per second) = **3.09**

So…

$$E = \frac{1}{2}(4 \cdot 10^{17})(3.09)^2 \approx 2 \cdot 10^{17} \cdot 9.56 \approx 9.56 \cdot 10^{17} \approx 1.91\ eJ$$

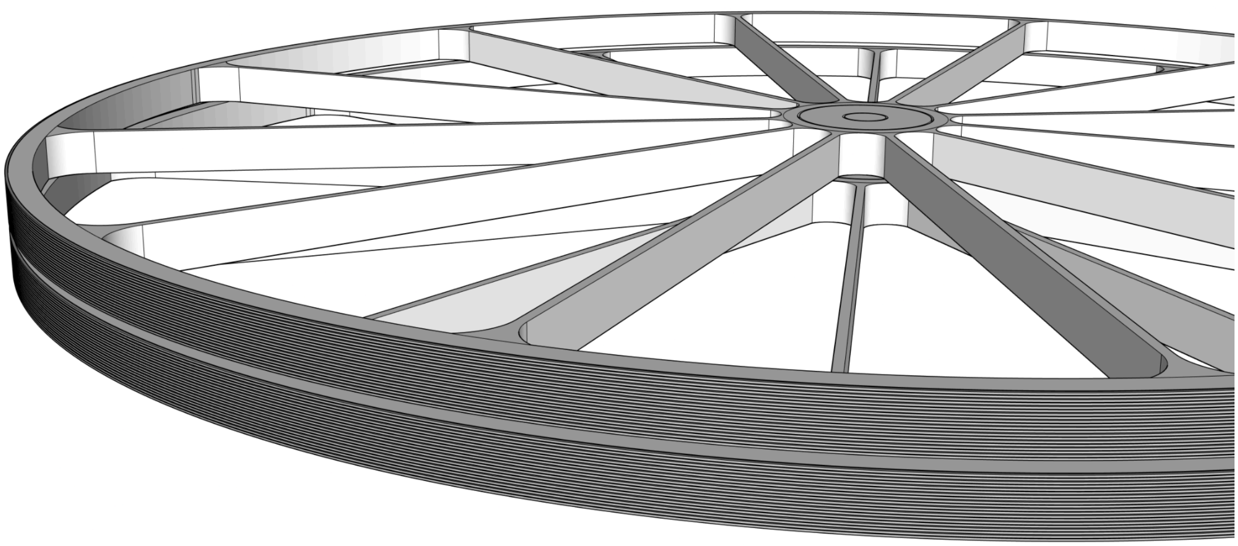
Python: Flywheel Inertia.ipynb

The 100 megaton flywheel rotating at 29.5 RPM stores **1.91 exaJoules** of energy. You'll recall that launching a 10 kiloton ship at 10 kilometers per second requires 500 TeraJoules of energy.

The flywheel has so much stored energy it could literally launch thousands of ships before its inertia is depleted. Likely this would be limited to some reasonable fraction of the stored energy and other actions can be taken to regain that momentum outside of payload captures. We'll discuss methods of orbital stationkeeping in following sections which can also be used for gaining rotational inertia.

Stacking Plates

Two counterrotating flywheels joined by a central shaft can transfer torque between them while canceling out gyroscopic precession. A 100 meter tall flywheel has track space for 10 tether reels and therefore 10 launch tethers. A pair of counterrotating wheels would double this. And why build one when you can build two for twice the price?



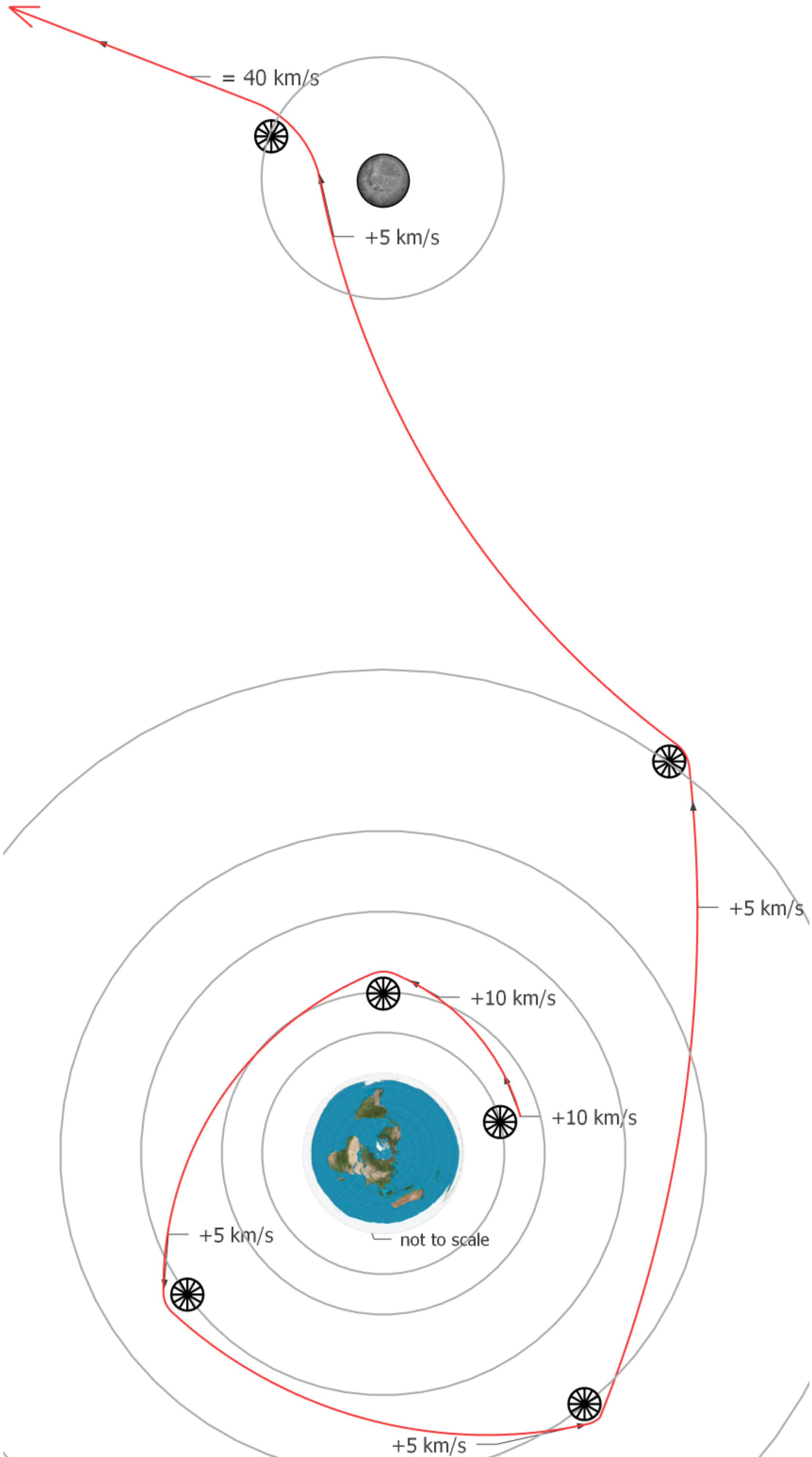
With the high width to height ratio of the flywheels, up to half a dozen flywheels can share an axel before stability is an issue. Stacking flywheels on a common axis allows them to exchange power and inertia and share stationkeeping infrastructure.

Relays and Teams

Sequential Boost

Interplanetary probes reach high velocities with multiple flybys of Earth and other planets, taking advantage of the Oberth effect. By sending the payload into an elliptical orbit, it can return for a second or third boost, raising the apoapsis each flyby with less force than would be required for a single high g fling. This is how planetary flybys are done with conventional space probes to save fuel but it can take years to attain the desired velocity.

If there are multiple momentum banks in orbit, sequential boosting can get a ship up to very high speed and launch it straight out of the system. The momentum banks needn’t be in line as they can accelerate and then swing the ship on course to the next MEB.


= 40 km/s
+5 km/s
+5 km/s
+10 km/s
+10 km/s
+5 km/s
not to scale
+5 km/s

In this case a ship leaving Earth receives its first boost from a momentum bank in medium Earth orbit. That momentum bank relays it to the next MEB with an initial velocity of 10 km/s. The next MEB in a higher orbit adds 10 km/s and relays to the next which adds 5 km/s and so on. The ship is already beyond escape velocity; the trajectory from one momentum bank to another would be ballistic until the final Earth orbiting momentum bank sends it off to the moon. Allowing it to fall into the moon's gravity well, the ship receives a slight Oberth acceleration before the Lunar orbiting MEB launches it out of the system with a final velocity of 40 km/s.

Additional momentum banks multiply the final velocity by dividing the force between them. MEBs at Lagrange points can provide the final acceleration as a payload departs or initial deceleration as a ship arrives.

This additive change in velocity has massive effects on transit times. If the distance traveled to Mars is 100 million kilometers, it will take 10 million seconds to get there at 10 kilometers per second. That's about 4 months. Not bad by rocket standards. If a relay network of momentum banks can boost that up to 40 km/s then it only takes 1 month to get to Mars and that can be mostly payload, not propellant.

Gateways

Multiple momentum banks in formation create arrays around ideal approaches between systems, like the L1 and L2 points. An array of banks can cooperatively pull payloads through the gap in the formation. L1 and L2 points are only metastable, requiring constant stationkeeping but the upcoming section on stationkeeping shows there are several options for stabilizing momentum banks propellantlessly.

Earth and Mars are in constant motion so the distance between them ranges from 55 to 400 million kilometers. Predictability is vital to the exchange of payloads between momentum banks and the functioning of the Momentum Exchange Network. At such a long distance a very slight misalignment in the trajectory could result in a huge miss. A momentum bank's orbit will change slowly due to effects like drag, perturbation, and recoil. To address this we should create gateways in and out of a system.

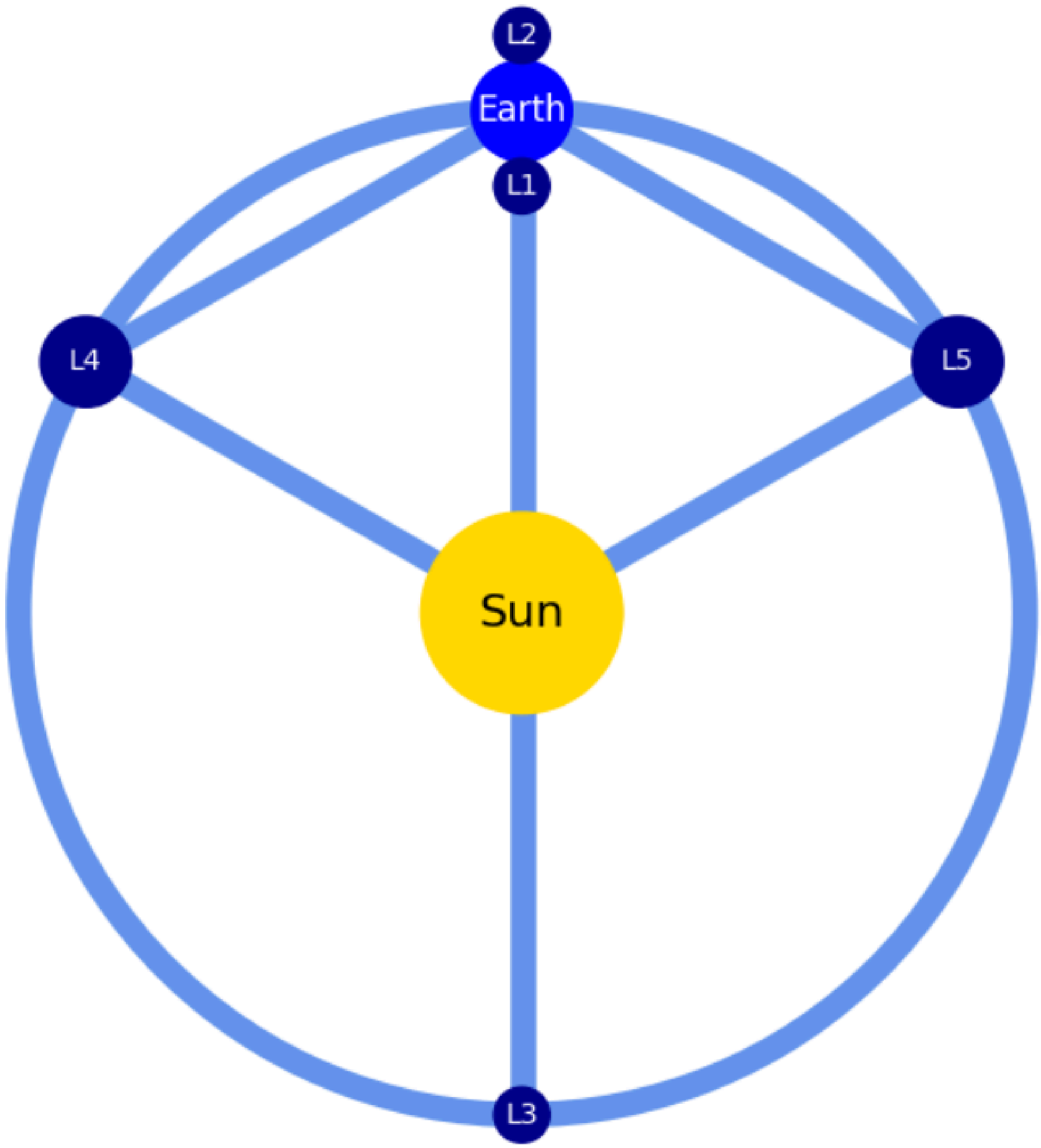
Lagrange Points

Lagrange points are stable coorbiting regions of space ideal for momentum exchange arrays. They are places where gravity and momentum cancel out and very little stationkeeping effort is required to remain in place.

The Sun's mass is vastly greater than the Earth's but, if we trace a straight line from the Sun to the Earth, there is a point where their gravities balance. This "L1" balance point is about 1.5 million kilometers from Earth. There is a complementary point opposite the Earth where the Earth and Sun's gravity combines to make a second point of stability, the "L2".

These points orbit the Sun with the Earth and remain fixed along the Earth/Sun axis. Because of their stable location on either side of Earth they make ideal gateways to entering and exiting the Earth/Luna system.

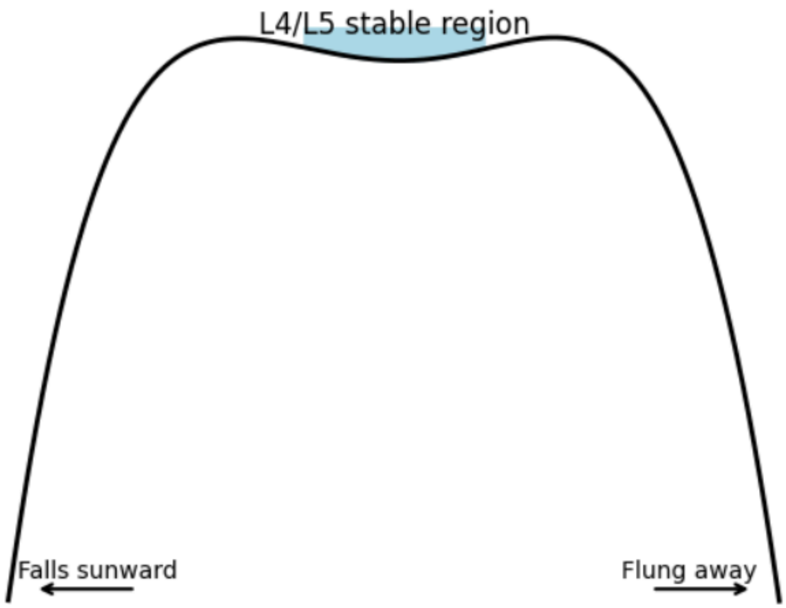
Approximate Earth-Sun Lagrange Points



L4/L5 Stability

Some regions of space are inherently stable, meaning that gravity and momentum cancel out in all directions and forces naturally combine to counter drift. The L4 and L5 Lagrange Points are such spaces.

Objects can and do naturally collect there and stay for thousands of years or longer. Asteroid (614689) 2020 XL5, which we fantasized about earlier, is one such object. It gets a little perturbed every time Venus goes by and in around 4 thousand years it will have had enough and just leave. So we better hurry.

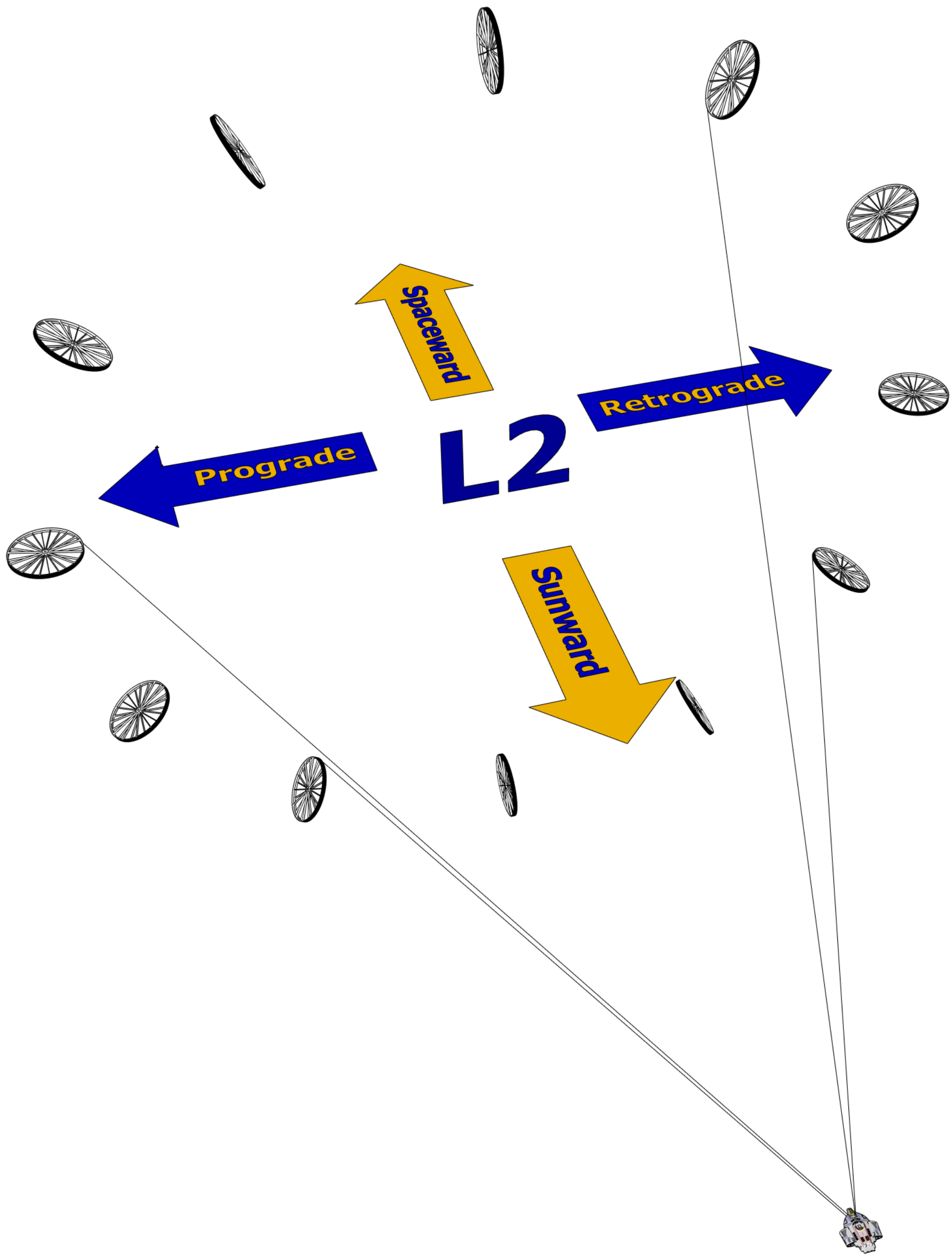


A momentum bank or space station L4 or L5 wouldn't need much stationkeeping. Think of it sort of like a pond on a hilltop with gently sloping edges on the inside but steep slopes on the outside. You can drift around inside the pond and the combined forces of gravity and momentum will tend to bring you back from the edges. If you go too far you'll fall downhill and end up in an unstable, elliptical orbit, which would be very bad. A ship or station can remain in the pond without using any fuel, making this an ideal location for a gateway array of momentum banks.

L1, L2, L3

L1, L2 and L3 are a slightly different matter; they require active stationkeeping along one axis, rather like log rolling. Imagine you are at the L2 and facing Earth. You have dynamic stability up and down and side to side but not forward or backward. If you fall forward, Earth's gravity pulls you in. If you fall backward, your momentum sends you off into space. So you have to actively balance yourself there. But it doesn't take much.

There must be a reliable target for ships arriving from other planets to aim at where there will always be a momentum bank. Logically the L1 and L2 Lagrange points are the entry and exit of a planetary system. An arriving ship needs only to pass through the gateway and get tugged onto the right path to intercept the destination MEB in planetary orbit. This is a large region of space so it would require a formation of MEBs to ensure that any transiting ship will be within tether reach.



Departing through an L2 Gateway Array. Not to scale.

With arrays of momentum banks at each Lagrange Point, a ship can pass through many arrays across space, gaining or losing momentum at each step. Logically, a ship wants to reach its maximum velocity before it enters the long gulf of interplanetary space between orbits and it accumulates the greatest velocity by exiting the system through the L2 heading spaceward or through L1 heading sunward. At the end of this paper we will see what happens when we optimize arrays for a very large launch mass and interstellar velocity.

Tethers

An online calculator for determining tether masses and final acceleration is available here: https://momentum.galenmatson.com/

There are a number of potential tether materials which currently exist but the material which makes this concept interstellar is graphene. Even 1 meter of pure graphene monolayer is an impressive yield today (2025) but manufacturing thousands of kilometers of atomically flawless graphene tethers does not seem far fetched with 30 to 100 years of advancement in materials science, chemistry, and space based manufacturing.

I refer to graphene as ‘Clarktech’ because it has properties that would certainly appear magical if we had no understanding of atomic physics. It can conduct with lower resistance than any metal at room temperature, it has a tensile strength 200 times greater than the strongest steel, and its melting point is far above that of any metal.

Due to graphene’s high strength to weight ratio, tethers thousands of kilometers in length are possible. Longer tethers are better for slower, gentler acceleration. Ships with people aboard cannot be subjected to more than a few g’s for long. In general, faster accelerations reach higher speeds in less time with less energy.

The cost of launching high mass payloads from Earth will be prohibitive in the absence of a space elevator but the momentum bank can make a major difference. Momentum banks in Medium Earth Orbit could potentially relieve all Earth launch vehicles of their second stage fuel and engine mass. The tethers are long enough to reach from low MEO to middle LEO. Reach a high suborbital trajectory on a reusable booster and hand off the payload to a momentum bank that can lift it to orbit or chuck it all the way to Mars.

Materials

Pulling things with ropes is prehistoric technology. Making ropes strong enough to catch spaceships is very new. Here are materials ranked by their **strength to weight ratio**, also known as **specific strength**:

material	tensile strength (MPa)	density (kg/m3)	specific strength
graphene	130000	2270	57.27
carbon nanotubes	63000	1500	42.00
boron nitride	33000	2000	16.50
Dyneema, Spectra (UHMWPE)	4000	950	4.21
Zylon (PBO)	5800	1560	3.72
Kevlar, Aramid	3620	1440	2.51
steel cable (EEIPS)	2160	7800	0.28

The astounding tensile strength of graphene cannot be overemphasized. Contemporary materials with a high strength to weight ratio will work at a diminished capacity. Conventional polymers could optimistically provide 1/10th the acceleration achievable with graphene.

Boron nitride deserves a mention at this point because it is also an incredibly strong monolayer with important differences with graphene. While graphene is an excellent conductor, boron nitride is an exceptional insulator. This will be important when we dive into the electrics because, in combination, graphene and boron nitride make conductors that are both the strongest and most conductive in the known universe, a combination I consider Clarktech.

Specialized Tethers

A momentum bank has several tether types optimized for specific purposes. Launch tethers would optimize for high and low g forces. Suitably engineered ships or containers could tolerate extreme gees that would turn humans into meat puddles. While this would economise on space there would be tradeoffs with passenger satisfaction. So launch tethers should be optimized for the g load acceptable by the payload for the final velocity desired.

Electrodynamic tethers, discussed later, optimize for length and conductivity. Radiator tethers would maximize their surface area, emissivity, and thermal stability. Extremely long and light leader lines can make an initial attachment that multiple tetherheads ride to the payload to attach heavier tethers, allowing multiple MEBs to pull in concert.

Tether Type	Dimensions	Design Priorities	Typical Use
High-G Launch Tether	Short (~100–500 km), thick	High tensile strength, rapid acceleration, heat resistance	Launching durable cargo at high g
Low-G Launch Tether	Long (~1,000–2,000 km), tapered	Minimized stress variation, passenger-safe acceleration, mass-efficient tapering	Launching crewed ships or fragile payloads at ≤3g
Electrodynamic Tether	Very long (≥1,000 km), wide & thin	High conductivity, low resistance, high surface area for cooling	Stationkeeping, orbit raising/lowering via Lorentz force
Radiator Tether	Long, very wide & thin	High emissivity, thermal conductivity, and surface area	Waste heat dissipation
Leader Line Tether	Extremely long (~5,000+ km), ultra-thin	Ultra-light, strong enough for gentle initial attachment	Connecting tetherheads to payload before main tether engagement
Gravity Gradient Tether	Long (variable), tapered or weighted	Mass at end, stability under tidal forces	Passive attitude/orbit stabilization, stationkeeping aid

High traffic momentum banks will have dozens of ships and payloads transiting their sphere of space at a given time and have dozens of tethers in use at once while regenerating their orbits and radiating waste heat. Having a diversity of tethers provides the right tool for the job.

Tether Length

The momentum bank applies a steady force to a length of tether until it runs out. We will determine the minimum tether length. To protect human passengers we must also limit the acceleration to 3 Earth gravities (g’s), which is similar to the force humans experience on a space shuttle launch or an exciting roller coaster. We furthermore cannot at any point exceed 50% of graphene’s tensile strength.

1 Earth g = 9.80665 meters per second squared

Acceleration (α) limit = $3\,g \;=\; 3 \cdot 9.80665\, m/s^2 \;=\; 29.41995\, m/s^2$

The kinematic equation calculates the velocity(v) achieved by accelerating(α) at a sustained rate for a certain distance(*L*):

$$v^2 = 2 \cdot \alpha \cdot L$$

Solving for length *L*:

$$L = \frac{v^2}{2 \cdot a}$$

Plug in our target velocity:

10 km/s = 10,000 m/s

$$L = \frac{(10{,}000\ m/s)^2}{2 \cdot 29.42\ m/s^2} \approx \frac{100{,}000{,}000 m^2/s^2}{58.84 m/s^2} \approx 1,699,527m \approx 1,700\ km$$

Python: Tether.ipynb

We would need **1700 kilometers** of tether to accelerate a payload at a constant 3 g's to reach 10 kilometers per second.

Tether Strength

It's important to know that our thin graphene ribbon won't snap under the strain of yanking a 10 thousand ton ship at 3 gravities. If we have a tether a meter wide and a centimeter thick, how strong is it?

We can figure that out by taking the cross sectional (*A*)rea of the tether and multiplying that by graphene's tensile strength, this will give us the maximum force(F_{max}).

$$F_{max} = tensile\ strength \cdot A$$

The tensile strength of graphene is 130 GigaPascals = **130 • 10^9 Pa**. Multiplying by the area of the tether in square meters will give us the maximum tensile strain in Newtons. The tether is 1 meter wide and .01 meters thick so 1 m * 0.01 m = 0.01 m^2.

$$F_{max} = 130 \cdot 10^9\ Pa \cdot .01\ m^2$$

$$F_{max} = 1.3 \cdot 10^9 N = 1.3\, GN\ (gigaNewtons)$$

The tether can withstand an absolute force of 1.3 gigaNewtons. To highlight how strong this is, a Nimitz class aircraft carrier weighs about 100,000 tons. Earth's gravity exerts a constant force of 9.8 meters per second squared. So the downward force of that aircraft carrier is almost 1 gigaNewton. This graphene tether could lift it.

1.3 gigaNewtons is the tether's breaking point, for a healthy safety margin we will use half this.

$$1.3 \cdot 10^9 N \cdot 0.5 = 6.5 \cdot 10^8 N$$

Python: Tether.ipynb

Therefore the maximum force we will put on the tether is **650 MegaNewtons**.
That's a lot of force. Is it enough? We can compare this to the force on the tether.

What is the force of 3 gravities on a 10 kiloton payload?
You'll remember from roller derby that force equals mass times acceleration:

$$F = MA$$

$$F = 10,000,000\, kg \cdot 29.41995\, m/s^2 = 294,199,500\, N$$

$$F = 294,199,500\, Newtons$$

Python: Tether.ipynb

Is the tether strong enough to withstand such a force?

650,000,000 - 294,199,500 = 355,800,500

Yeah it can, and then some. But that's not the whole story because such a long tether is massive and it has to pull its own weight in addition to the weight of the payload. Let's see what happens when we take this into account.

Tether Mass

The mass of a multimegameter graphene ribbon is significant, though it diminishes as the tether is reeled in. For a tether of uniform width and thickness the tether mass (m_t

) equals the (*L*)ength times the (*w*)idth times the (*t*)hickness times the density of graphene (d_g) in kg/m^2.

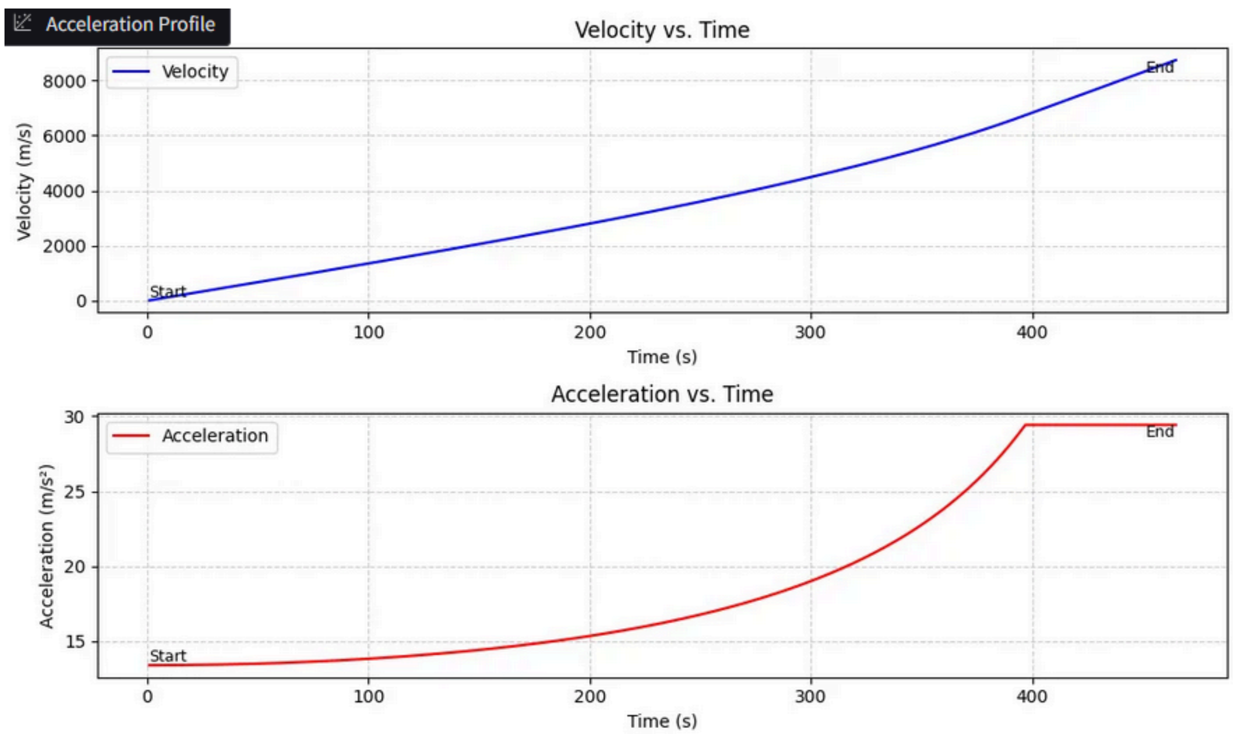
Our tether is 1,700,000 meters long, 1 meter wide, and 1 centimeter thick. The density of graphene is 2270 kg/m^3.

$$m_t = L \cdot w \cdot t \cdot d_g = 1,700,000m \cdot \ 1m \cdot \ .01m \cdot 2270\ kg/m^3$$

$$m_t = \ 38,590,000\ kg$$

A 1700 kilometer tether 1 meter wide and 1 centimeter thick has a mass of almost 40 kilotons! That quadruples the mass of the payload.

The tether mass must be added to the payload mass, increasing the tensile strain. A uniform tether cross section would be weaker than necessary at the reel or stronger than necessary at the payload, resulting in a mesa shaped acceleration profile:



A tether with uniform width and thickness cannot pull by the full 3g's we desire until most of its mass is reeled in. The area of the tether is too small at the start and too large at the end. How can we improve this?

Tapering

A far more efficient tether is tapered to handle the same force at the reel as it does at the tetherhead. To taper the tether we first need a target tensile strength so the strength always exceeds the stress at any point.

Growth Rate

For this we need to come up with an exponential that fits the curve of increasing tether thickness by relating the thickness to the force supporting the mass below, going from the tetherhead to the reel.

Let's restate our values:

Graphene density (gD) = **2270 kg/m^3**

Acceleration (a) = **29.41995 m/s^2**

Tether Length (L) = **1,700,000 m**

Max strain (sM) = **6.5·10^{10} Pa**

We'll calculate our exponent of growth (exp) by multiplying the density of graphene (gD) times the acceleration (a) times the length of the tether (L) and dividing that by the maximum stress (sM) on the tether:

$$exp = \frac{gD \cdot a \cdot L}{sM} = \frac{2270 \cdot 29.41995 \cdot 1{,}700{,}000}{65{,}000{,}000{,}000} = \frac{113531587050}{65{,}000{,}000{,}000} = 1.7466398008$$

Mass

We use the natural logarithm e, which is known as Euler's number. It was initially derived for torturing math students but found widespread use calculating curves with a constant rate of change like compounding interest but it works just as well for calculating compounding mass.

Euler's number (e) = **2.718281828459045**

Payload mass (pM) = **10,000,000 kg**

That total mass of the tether is the starting mass, which is just the payload, times e to the power of our exponent of change minus 1:

$$Tether\ mass = pM \cdot (e^{exp} - 1) = pM \cdot (2.718281828459045^{1.7466398008} - 1)$$

Solving the exponential yields the coefficient of growth: **5.7352985158**

$$Tether\ mass = pM \cdot (5.7352985158 - 1) = pM \cdot 4.7352985158$$

Tether mass = 10,000,000 kg · 4.7352985158 = 47,352,985 kg = **47.35 kilotons**

Python: Tapered Tether.ipynb

In this scenario the tether itself weighs almost 5 times the payload alone. To keep things simple our example calculations for the energy of accelerating the ship didn't take this into account. This will require a great deal more energy from the momentum bank. We'll account for this in later sections on the Reel design.

Thickness

The thickness at the tetherhead equals the payload mass (pM) times the acceleration (a) divided by the strength of graphene with a 50 percent safety factor (sM) times the width (tw).

$$starting\ thickness = \frac{pM \cdot a}{sM \cdot tw} = \frac{10000000 \cdot 29.41995}{65000000000 \cdot 1} = \frac{294199500}{65000000000} = 0.0045261462$$

The starting thickness at the tetherhead is only 4.5 millimeters. We'll scale it just like we did with the mass to find the thickness at the reel. We already raised Euler's number by our exponent of growth in the tether mass calculation which was based on the tether length of 1700 km, so we know the growth rate is **5.7352985158**.

$$ending\ thickness = starting\ thickness \cdot growth\ rate$$

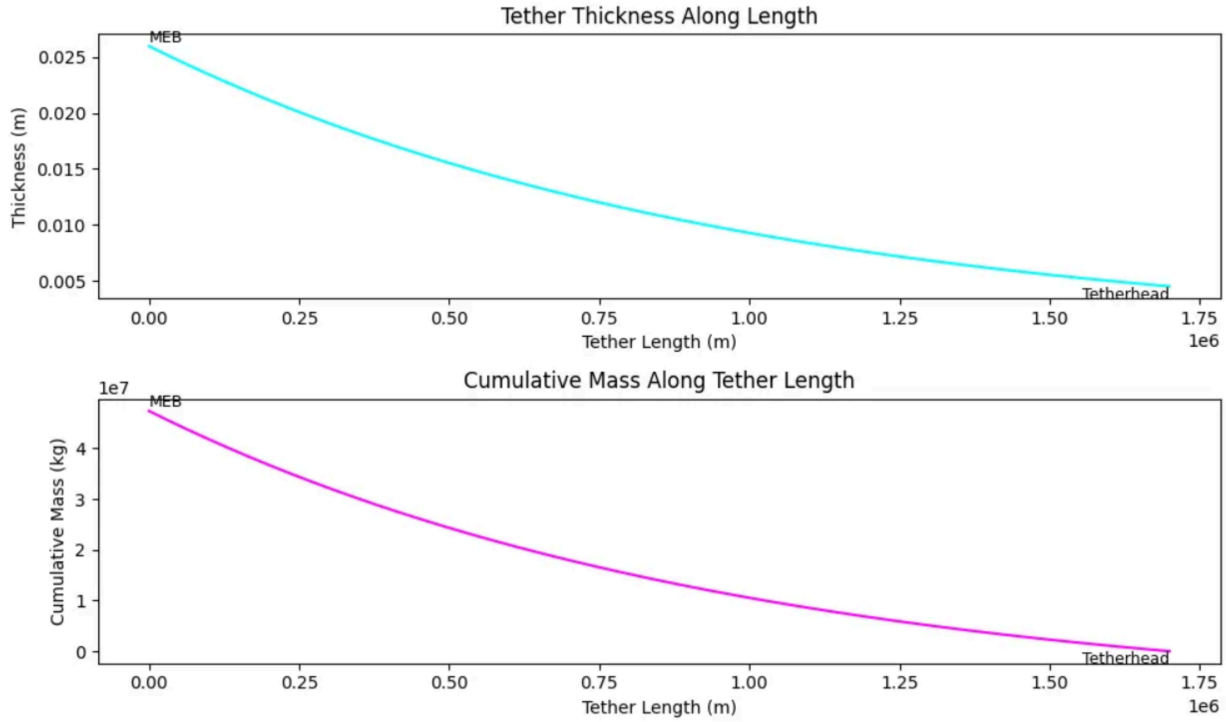
$$ending\ thickness = 0.0045261462 \cdot 5.7352985158 = 0.0259587996 \approx 0.026m$$

Python: Tapered Tether.ipynb

So the thickness at the reel is about 26 millimeters, equivalent to a metric thumb width.

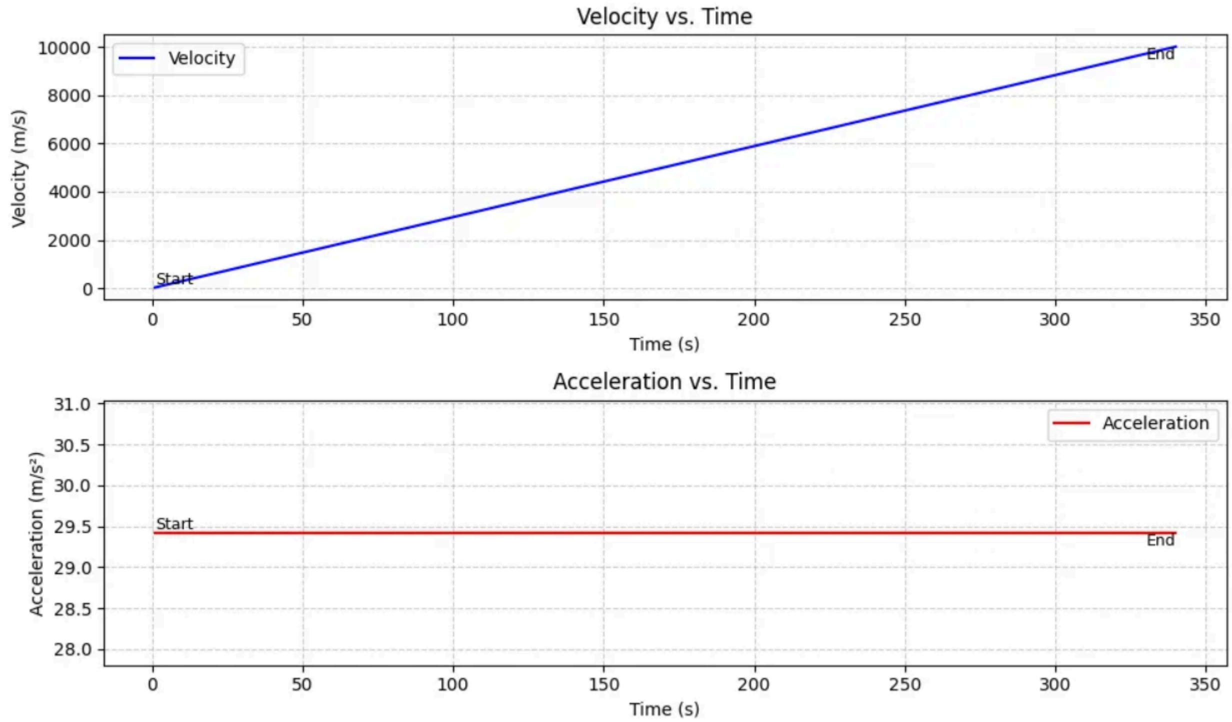
Tether Profile

According to the scientific papers I tell everyone I read there should be graphs so here is a plot of the tether thickness and mass:



The area under the curve is the total mass of the tether we calculated previously.

Since the tether is now strong enough to support the full force for the duration this yields a linear increase in velocity and a uniform acceleration throughout the pull:



This results in higher final velocity without waste mass. All scenarios from hereon assume tapered launch tethers.

Free Launch

Momentum banks transact in kinetic energy, using their mass as an anchor point in space which can be pushed and pulled on without the wild changes in velocity of a smaller object. But the tugs and shoves accumulate and an MEB wandering out of reach for incoming payloads would be disastrous.

The counterparty in a momentum exchange must reliably know, potentially years in advance, the location of the destination momentum bank when it launches a payload. To keep their location predictable requires constant adjustments to speed, direction, and orientation known as stationkeeping.

The simplest method is to balance outgoing kinetic energy with incoming kinetic energy. This cannot be guaranteed, especially over interplanetary distances and long travel times. It also might not be preferable. A new colony will receive a steady stream of supplies and materials but will have little to send back until it is well established. Its

MEB will absorb momentum until its orbit becomes too wide or its flywheel spins beyond its mechanical failure point.

Payloads arriving out of plane or off center will cause a momentum bank to slew and precess. The changes in velocity will increase or decrease the MEB's orbital velocity which will raise, lower or elongate its orbit, tilt its orbital plane, and change its orbital period.

These changes in orbit and orientation must be constantly counteracted. Below are several methods which do this for free. If all the energy for launching ships across the solar system can be gathered from the environment then that's as close to a free launch as we'll ever get.

Economics

The simplest method of balancing momentum banks is economics. Arriving ships receive momentum credits for the energy they bring and pay the difference when they depart. If the price for momentum at their destination is higher than the cost at their origin, then merchants will naturally arbitrage the imbalance so long as there is enough buffer in the system.

If a given MEB has launched a great deal of payload out of its system and lost rotational energy and orbital momentum the best way to restore it is by capturing payloads. Momentum banks can coordinate their activities using prices; offering more for the momentum of inbound payloads at higher velocities and along specific trajectories. They can likewise charge more for launches that deplete their spin and momentum.

This results in interesting energy economics. In the stationkeeping sections below you will see how momentum can be acquired for free. This means some momentum banks can run a positive kinetic balance and essentially export energy as kinetic payloads.

The availability of propellantless propulsion for regenerating orbital and rotational inertia necessarily results in price spreads between planets and regions. MEBs close to the sun can deploy large solar sails for constant and free boost.

Inside the strong magnetic field of a large planet, momentum can be regained electrodynamically. Not all planets have sufficient magnetic field strength; Mercury, Venus, Mars, and dwarf planets like Ceres, Vesta, and Pluto have no internal dynamo, and therefore no strong magnetic field an MEB can push on.

At the Lagrange Points, specifically L3, L4, and L5, there are no nearby planets. Beyond the orbit of Jupiter, sunlight and solar wind are too diffuse to economically gather momentum. Gravity gradients can be intelligently exploited but these maneuvers will be very slow. These energy poor regions will have inherently higher costs for energy, materials, and transportation.

Nuclear engines with high efficiency can provide active stationkeeping but require large amounts of propellant. There's not much propellant naturally at Lagrange Points so fuel tanks will have to be imported from the gas giants. Fully loaded hydrogen tanks can mass kilotons and can carry a large amount of momentum and the distribution of gas giants creates favorable vectors for stationkeeping by intercepting such large payloads.

Energy availability drastically affects the economics of momentum exchange. If momentum can be generated for free, discounting the production and operating costs of the MEB, the cost of space travel can approach the cost of energy. Let's see if there is such a thing as a free launch.

Electrodynamic Stationkeeping

Graphene is highly conductive and this has massive implications. An important potential application is electrodynamic propulsion in which an electrified tether repels off of the Earth's magnetic field, accelerating a satellite or spacecraft without propellant, only electricity is required. And it does require a lot.

This form of propellantless acceleration is already well characterized and tested by many organizations both private and public such as NASA, JAXA, ESA, and academic missions. These tests demonstrated the functionality and practicality of using electrified tethers to change velocity and orientation or to harvest energy from Earth's magnetic field. We will take this concept to its logical extreme.

In the presence of strong magnetic fields the momentum bank can unreel extremely long lengths of tether and drive high currents through it to change speed and direction. Lorentz acceleration will either boost or brake the MEB in orbit of a suitable planet like Earth, Jupiter, or Saturn. This is a form of propellantless stationkeeping that can stabilize the MEBs in planetary orbits. It requires a strong magnetic field so it will not work around every planet or moon or Lagrange point.

To illustrate the feasibility of electrodynamic stationkeeping lets create an example case using a tether that is 1000 kilometers, the MEB weighs 100 megatons, Medium Earth Orbit (MEO), and we want a constant acceleration. This can be a small acceleration, given the mass involved, but cumulative.

We can disregard the power source and waste heat, these issues are addressed in later sections. We can disregard the direction for now, we're interested in the magnitude.

Current Carrying Capacity

Let's first get the resistance and melting point of graphene and derive from that the maximum current. To optimize for high current we'll create a tether with more surface area for radiating heat. The electrotether will be a 10 meter wide, .1 millimeter thick, 1 megameter long ribbon. We can get the maximum current carrying capacity of the ribbon by limiting the resistive heating to 50 percent of the sublimation temperature of graphene and finding what amperage would heat the tether to this temperature.

Tether

Graphene has an incredibly high melting point or rather *sublimation* point because it does not go from solid to liquid but evaporates directly to a gas at 3600C, a higher melting point than tungsten (3,422C). To avoid damage we'll limit the temperature of the electrotether to 50 percent of its max temperature: **1800C**.

Length (*L*) of the tether = **1,000,000 m**

Area (*A*) of the tether = width * thickness

$A = 10m \cdot 0.0001m$ = $\mathbf{0.001m^2}$

Resistance

Resistance in a conductor is equal to the resistivity (ρ) of the material times its length (*L*) divided by its cross sectional area (*A*):

$$R = \frac{\rho \cdot L}{A}$$

The resistance of graphene at room temperature is 1×10^{-8} Ohm (Ω) meters. This extremely low resistance is better than the best metallic conductors like copper or silver.

We need the total resistance of the electrodynamic tether to determine the total heat produced by the high currents we will apply to it. To get that we'll multiply the resistivity by the tether length and divide that by its area.

Python: electrodynamic tether.ipynb

$$R = \frac{1 \cdot 10^{-8}\Omega m \cdot 1{,}000{,}000m}{1m \cdot 0.001m} = \frac{0.01}{0.001} = 10\Omega$$

10 Ohms of resistance over a length of a million meters is very low, the tether will be able to carry an extraordinary amount of amperage, limited by its melting point.

The resistance of graphene, like any conductor, will rise with temperature. Due to its unique structure, graphene's resistance does not rise as quickly as metallic conductors. At 1800C the resistance might increase by 2 to 5 times, which would result in a resistivity comparable to copper at room temperature.

Max Current

To find the maximum current we must find out at what amperage our tether will exceed half its melting point (1800C). To do that we need to factor in the tether's emissivity. Anything with a temperature above absolute zero glows. This is called blackbody radiation and its intensity increases rapidly with temperature according to the Stefan-Boltzmann law:

$$P = \epsilon \sigma A T^4$$

Meaning the radiation in Watts is equal to the emissivity times the Stefan-Boltzman constant times the surface Area times the Temperature to the fourth power. A fourth power exponential is a lot, which we'll see shortly. A very high temperature will result in a lot of radiated energy.

P is the radiation in Watts.

ϵ is the emissivity from 0 to 1. Emissivity of 0 being nonemitting, 1 being a perfect blackbody. Based on available information we'll use a conservative emissivity value of **0.9** for our graphene tether. Matsumoto et al. (2013) have shown experimentally that surface nanostructure optimization of graphene can achieve emissivities over 0.99 at a temperature up to 2500K, across a wide spectrum, approaching the theoretical optimum of a perfect blackbody.

σ is the Stefan-Boltzman constant (**5.670374419...×10^{-8}**)

A is the surface area of the tether. Since both sides of the ribbon are radiating the surface area is double its width times its length: 2 * 10m * 1,000,000m (**20,000,000m^2**). The thickness does contribute slightly to its surface area but we'll disregard it for now.

T is the temperature of the black body. In this case our tether will operate up to half its melting (sublimation) point, 1800C (**2073K**).

Emissivity

To get the maximum current we need to calculate the power the ribbon will radiate at 1800C (2073K) in Watts. Then we can use basic electrical engineering to figure the number of Amps we can apply to the ribbon and from that determine the acceleration the electrodynamic tether can create for reboosting or deboosting the MEB.

Python: electrodynamic tether.ipynb

Restating the Stefan-Boltzman equation:

$$P = \epsilon\sigma A T^4$$

Make our substitutions:

$$P = 0.9 \cdot 5.670374419 \cdot 10^{-8} W/m^2/K^4 \cdot 20,000,000\, m^2 \cdot (2073)^4$$

Starting at the end, for the Stefan Boltzman equation we use the 4th power of the temperature in Kelvin.

$$T^4 = (2073)^4 = 1.8467037 \cdot 10^{13}$$

Plugging that in at the end and multiplying the Stefan Boltzman constant by the coefficient of emissivity our equation is now:

$$P = (0.9 \cdot 5.670374419 \cdot 10^{-8}) \cdot 20,000,000 \cdot 1.8467037 \cdot 10^{13}$$

$$P = 5.10333698 \cdot 10^{-8} \cdot (20,000,000 \cdot 1.8467037 \cdot 10^{13})$$

$$P = 5.10333698 \cdot 10^{-8} \cdot 3.6934074 \cdot 10^{20}$$

$$P = 1.8848703 \cdot 10^{13}$$

$$P = 18,848,703,000,000\, Watts$$

The tether can radiate nearly **19 Terrawatts** of heat at half its sublimation temperature.

This also implies that graphene ribbons with high surface area can be employed as radiators for the MEB's power source or for other applications like cooling space stations and spaceships with gigawatt power sources quite efficiently and with far less mass than traditional radiators.

This very high heat rejection with low electrical resistance gives us the ability to drive massive Amperages across the ribbon. We'll find the maximum amperage in the next section and from that discover how much Lorentz acceleration that would create in Earth's magnetic field at MEO.

Amperage

Python: electrodynamic tether.ipynb

Joule's law relates the radiated power in Watts to the square of the current times the resistance.

$$P = I^2 R$$

We want the amperage so we can calculate the Lorentz force. Solving for current:

$$\frac{P}{R} = I^2$$

We'll just smack resistance over to the power side, invert the square, flip it around, and here's how we get our amperage:

$$I = \sqrt{\frac{P}{R}}$$

Fill in our values:

$$I = \sqrt{\frac{1.8848703 \cdot 10^{12}}{10}}$$

$$I \approx 1,372,905\ Amps$$

1.37 MegaAmps is a very high current, next we'll calculate the Lorentz acceleration of the tether in Earth's magnetosphere.

Lorentz Force

To calculate the acceleration we multiply our **1.37 MegaAmps** by the tether length (**1,000,000m**) and the approximate magnetic field strength of the Earth at 2000 km altitude (**17 microTeslas**).

Python: electrodynamic tether.ipynb

$$F = ILB$$

Where:

F = the force in Newtons

I = the current in Amps

L = the tether length in meters

B = the magnetic field strength in Teslas

$$F = 1,372,905.78701 \cdot 1,000,000 \cdot 0.000017 = 23,339,398.3792\ Newtons$$

$$F = 23.34\ MegaNewtons$$

That's a tremendous force! For comparison, the Saturn V moon rocket produced 35 MegaNewtons of thrust at liftoff. The force on the tether would be about 2/3rds the force of the Saturn V.

Acceleration

Python: electrodynamic tether.ipynb

With that much force, how much does it move a 100 megaton momentum bank? Acceleration is force divided by mass:

A=F/M

$$A = 23,339,398.3792N/100,000,000,000kg = 0.000233393983m/s^2$$

With that incredible force countered by a badonkadonkulous mass, the momentum bank will experience a constant acceleration of only .002334 m/s². That doesn't sound like a lot but a constant force adds up. There are 86,400 seconds in a day. Change in velocity (Δv) equals acceleration over time:

$$\Delta v = a \cdot t = 0.000233393983\, m/s^2 \cdot 86,400s = 20.1652385955264\, m/s$$

This is significant because it means that, even at Medium Earth Orbit, Electrodynamic Stationkeeping can reboost the momentum bank by **20 m/s per day**.

Electrodynamic Stationkeeping

In our test case above, every 10 kiloton launch vehicle gains 10 km/s while the momentum bank loses only 1 meter per second. This means the momentum bank can launch over 20 ships per day, regaining that momentum from the Earth's magnetic field. That comes out to a launch every hour and 20 minutes. Launching 20 ten kiloton ships represents 200 kilotons of mass leaving the Earth/moon system every day, headed for Mars, the Belt, Jupiter, and other human settlements.

In case this isn't landing with you, that's enough mass to build a space station the size of Manhattan every few months.

There will, naturally, be significant conversion losses, heat losses, friction losses, resistance losses, maintenance, etc.. Even if the real number is only a tenth of that it still opens the solar system to economic travel.

Not every planet has a magnetic field. So electrotethering has moderately limited application but many of the planets we care about have really strong fields. Jupiter's magnetic moment is over 20,000 times Earth's, it extends very far into space. If we could look up and see Jupiter's magnetic field it would appear larger than the moon. Jupiter's magnetic field is so strong its moon, Io, acts like a colossal electrical generator. A current of 3 million Amps flows between Io and Jupiter's upper atmosphere.

We can do a lot with 3 million Amps.

What are the field strengths around the other planets?

Planet	Approximate Surface/1-bar Magnetic Field Strength (relative to Earth's ~30-60 μT at surface)	Magnetic Moment relative to Earth	Notes for Electrodynamic Stationkeeping Potential

Mercury	~0.002 - 0.007 μT (at equator)	~0.0004 - 0.0006	Almost nonexistent however, the Sun's magnetic field at Mercury's orbit is 25 nT 🤔
Venus	Nonexistant except for some induced magnetosphere	Effectively 0	Meh 😤
Earth	25 - 65 μT (average ~30 μT at equator, up to ~65 μT at poles)	1 (reference)	Sufficient
Mars	Some slight local field strength, 100x Mercury but otherwise dead.	Effectively 0 for global field	Nope 😕
Jupiter	~420 μT (at equator, 1-bar level); ~1,000-1,400 μT (polar regions)	~20,000	Colossal 😯
Saturn	~21 μT (at equator, 1-bar level)	~580	The large Magnetic Moment should create a strong enough field for MEBs beyond the ring system.
Uranus	~23 μT (average at 1-bar level, but highly asymmetric and offset from center)	~50	Good but the MEB orbits will have to match the wonky axial tilt to cross the field lines.
Neptune	~14 μT (average at 1-bar level, highly asymmetric and offset)	~25	Also wonky but its so cold everything can be superconducting 🤯

The tether can be further optimized to be wider, increasing its surface area and emissivity which allows for even more current while staying well below its sublimation point. Resistance can also be lowered by increasing its thickness. Multiple electrotethers in different geometric configurations can be used for tangential acceleration, canceling out unwanted yaw or precession, or other stationkeeping functions.

Electrotethers can be significantly optimized for greater, sustained accelerations. Effectively transferring energy from magnetospheres to kinetic payloads or, in effect, from core rotation to spaceships. The strength of the Sun's magnetic field at Mercury is about a hundredth the strength of Earth's magnetic field at MEO, and that ain't bad. That represents a massive sphere of space with a magnetic field powerful enough for a slight but constant propellantless acceleration.

Lightsails

Like many of the best things in life, sunlight is free. Photons do not have mass but they do have momentum. The moment a photon is emitted by an atom, the atom experiences recoil. If the photon reflects it imparts twice the momentum than if it is absorbed.

A large enough solar sail can stabilize the MEB in a solar orbit and keep it oriented and in place without propellant. This means that satellites such as momentum banks can anchor in solar orbit just about anywhere in the inner system or constantly reboost decaying orbits.

Sunlight's meager momentum means the solar sails will have to be huge. Hundreds or thousands of square kilometers, even close to the sun. Solar radiation diminishes rapidly according to the inverse square law. At double the distance, there is 1 quarter of the light. Solar sails eventually become futile because inverse square losses require inverse inverse square growth.

A graphene lightsail can be astronomically large while still being technically possible. This table shows the solar irradiance and radiation pressure at each orbit in the inner and mid system and the sail area required to accelerate an MEB by 20 meters per second per day, equivalent to the reboost of the electrodynamic tether in the previous section.

Here's the irradiance and light pressure at planetary orbits from Mercury to Saturn.

Orbit	Mean distance (AU)	Solar irradiance (W m^{-2})	Light pressure(μPa)
Mercury	0.387	9 090	60.7
Venus	0.723	2 605	17.4
Earth (reference)	1	1 361.6	9.08
Mars	1.524	586	3.91
Asteroid belt	2.5	218	1.45
Jupiter	5.203	50.3	0.336
Saturn	9.537	15	0.1

Sunward momentum banks have the additional ability to export solar power as kinetic energy. Instead of using light pressure from the sun for changes in orbit like a typical light sail, a momentum bank can use an unbalanced sail to generate tangential acceleration which it can store as angular momentum in its flywheel. It can transfer this banked momentum to spaceward payloads to export dispersed sunlight as concentrated kinetic energy.

Handwaving the rigid support and focusing on the sail properties alone, lets design a sail that matches the launch cadence of the electrotether. The electrotether can reboost the station by a cool 20 m/s per day.

To find the area of sail we need to match the lightsail propulsive force to the electrotether acceleration. We previously calculated the force from the electrotether as 23.34 MN, **$23.34 \cdot 10^6$ N**.

To find the size of a light sail at Earth's orbit we need the value for light pressure from the table above: **9.08 µPa**. Dividing the acceleration force by the light pressure we get:

$$A = \frac{23.34 \cdot 10^{6}\, N}{9.08 \cdot 10^{-6}\, N/m^{2}} = 2.38163265 \cdot 10^{12}\, m^{2}$$

Converting from square meters to square kilometers:

$$\frac{2.38163265 \cdot 10^{13}}{1000^{2}} = 23,816,326.5\, km^{2}$$

Python: lightsail.ipynb

At Earth's orbit, a light sail to boost a 100 megaton MEB by 20 m/s per day would be a 1600 kilometer wide square or a circle 1800 kilometers across. Which would block out half the full moon (3475 km).

Orbit	Light pressure (µPa)	Sail size (km^2)	Square sail length (km)	circular sail diameter (km)
Mercury	60.7	381,353	618	697
Venus	17.4	1,330,353	1,153	1,301
Earth (reference)	9.08	2,549,356	1,597	1,802
Mars	3.91	5,920,242	2,433	2,746
Asteroid belt	1.45	15,964,240	3,996	4,508
Jupiter	0.336	68,893,298	8,300	9,366
Saturn	0.1	231,481,481	15,215	17,168

A sail made of graphene or even a conventional polymer can easily scale to these sizes and the acceleration force is manageable. Solar sails are steerable by altering the sun angle and controlling the shape and orientation can generate torque reaction control or adding spin to the flywheel.

Momentum banks with large solar sails in solar orbits can bank energy for months or years that they impart to ships leaving the solar system, at the end of this paper is a proposal for reaching interstellar velocity.

Momentum Exchange Mechanics

You can see at this point that the basic physics work if you allow for the assumptions made. This section gets into finer detail on the parts of the system that allow momentum exchange to work at the tremendous energies envisioned.

We've been using a simplified example case and now we're getting into the gritty specifics. If you think you've got the concept, you can stop here and enjoy the rest of your day. I encourage you to read on because we're going to do some megascale engineering.

I'll try and keep it streamlined but you'll soon find out this design is far more powerful than what has been suggested so far and the losers that just closed this tab will never know.

Power

Tremendous energy can be stored both kinetically and electrically and the combination of the two gives the momentum exchange bank incredible power. With some likely improvements in technology scaled up it is possible to reach interstellar speeds and wing colony ships off into the galaxy.

High velocity launches and stationkeeping capabilities require extremely high, sustained amperages. Electromagnetic accelerators can boost payloads far beyond what a mechanical application of force can achieve. The momentum bank itself can convert between kinetic energy and electrical potential like an orbital scale transformer.

Fusion is an ideal power source in the time frame considered here (decades) and I include estimates of fusion power but there are excellent options without it such as solar and nuclear fission.

Source	Estimated output	Notes	More info
Solar	10+ GW	Efficient, scalable, bulky	Triple-junction solar cells

Fission	1-100 GW	Proven, scalable with radiators	Atomic Rockets - fission
Fusion	10-1000 GW	Very scalable with advancements	Atomic Rockets - fusion

An often overlooked engineering challenge with fission and fusion spaceship propulsion is the heat load. Even assuming high conversion efficiencies the waste heat would amount to gigawatt levels and that must be radiated away to keep the reactor from melting. I show in the following sections on electrodynamic tethers how a momentum bank can handle tremendous waste heat so I won't address it here.

Existing solar panels can achieve efficiencies above 30 percent. Meaning that 1000 Watts of solar irradiance on a 1 square meter panel would produce 300 Watts. The light pressure on such a large surface area would impart a minor but useful acceleration analyzed in the upcoming section on light sails.

An MEB would have 2 solar arrays for balance, 1 above the disk and 1 below. If they are sized similarly to the flywheels they would have a surface area equal to pi times the radius squared. The radius is 2000 meters. Just some napkin math here:

$A = \pi r^2 = 3.14159 \cdot 2000^2 = 12{,}566{,}360\ m^2$

Each array would have an area of 12.5 million square meters. Solar irradiance in Earth orbit is 1361 watts per square meter (W/m^2). We multiply that irradiance by the efficiency (30%) and the surface area doubled for 2 arrays.

$W = 1361 \cdot 0.3 \cdot 12{,}566{,}360 \cdot 2 = 10{,}261{,}689{,}576$

That's **10 Gigawatts**. Solar power could be sufficient at Earth but solar power decreases rapidly with distance from the sun. To reach useful power levels in the inner solar system we do not need exotic or far tech energy systems, existing solar panels in large arrays can do the job.

Nuclear energy will be a requirement far from the sun. Proposed fusion reactors for spaceship drives range up to the terawatts. The gas giants likely have abundant fusion fuels and, for a momentum bank, the bulk of a fusion reactor would be a good thing.

Waste heat generated by any power source of this magnitude will be immense. The radiative cooling capability of the MEB is also immense, detailed in the section on Emissivity.

Graphenide Conductors

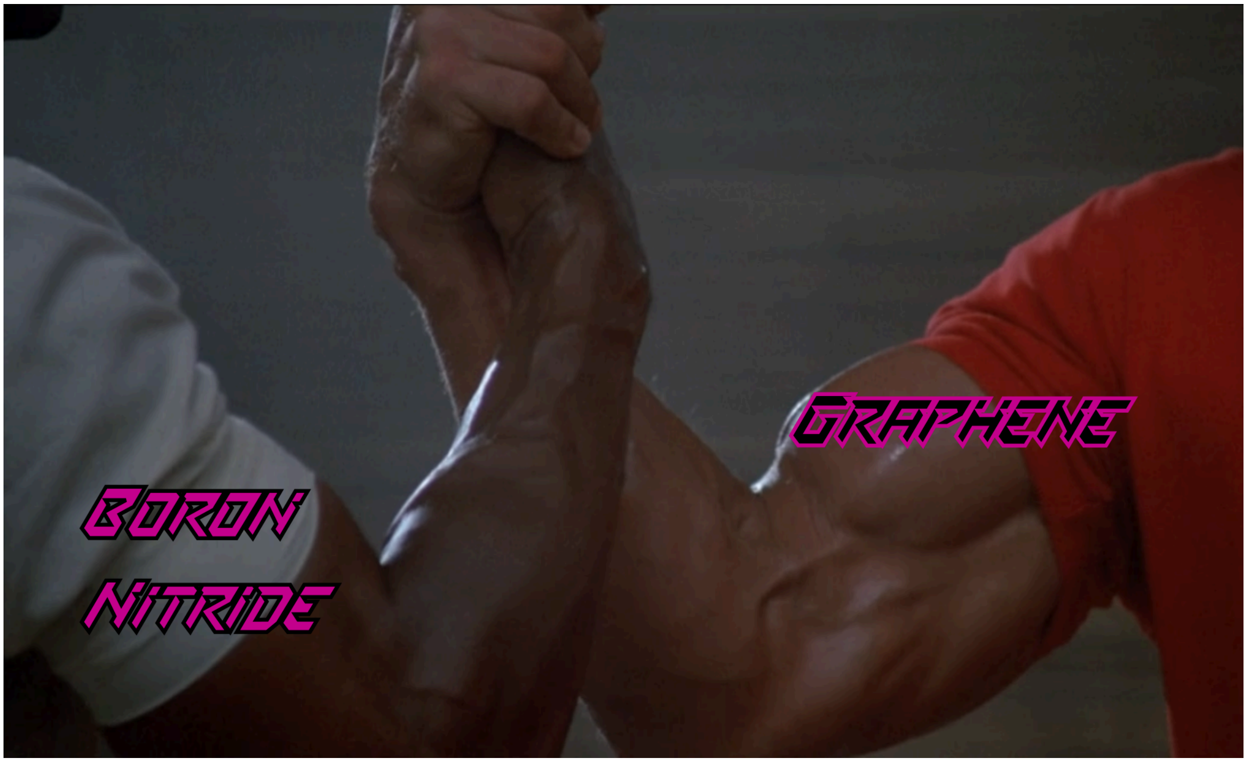
The extreme power levels and mechanical stress we're envisioning necessitate something better than copper wire to carry our current. Current, in electrical engineering, literally refers to the movement of electrons. One Amp is about 6.24 quintillion electrons per second.

In a good conductor they flow like a chill stream. Resistance is basically the friction the electrons experience as they move. Impurities, voids, and vibrations in the conductor are like adding rocks, turns, and turbulence in the stream; it impedes the flow and things start getting bumpy. This resistance creates heat. Heat ruins everything. It represents wasted power. Heat increases resistance, creating more heat in a runaway feedback that will melt your conductor if you leave the throttle open.

Conveniently, the strongest known material is also the best known conductor. Two dimensional graphene has the lowest measured resistance at room temperature, better than the best metallic conductor, silver. This is thanks to carbon's electron configuration and the molecular structure of graphene. Carbon can make 4 bonds. In graphene it makes 3, forming tidy triangles with its 3 nearest neighbors and organizing into a beautiful hexagonal lattice, like a honeycomb. This leaves one electron free per carbon atom giving graphene the highest known charge carrier mobility, meaning how easily the electrons can move between atoms and, on a large scale, through the tether or wire.

The conductivity of graphene can be enhanced by sandwiching additional charge carriers such as lithium between layers. Graphene is superconductive at ultra low temperature and recent experiments have raised its critical temperature significantly. A superconductor with 100 times the strength of steel will be useful for containing dangerously strong magnetic fields and operating at extreme velocities.

Such a great conductor needs a great insulator. Boron nitride is the perfect complement to graphene. As a monolayer it also forms a perfect hexagonal lattice of alternating boron and nitrogen atoms. It has incredible tensile strength and, most importantly, it's an exceptional insulator. Boron nitride and graphene together are like that awesome scene from Predator where Carl Weathers and Arnold Schwarzenegger shake hands.



Encapsulating graphene in boron nitride creates a wire with Clarktech capabilities. Super strong, super conductive, and excellently insulated. I call this combination Graphenide. That was the best I could come up with squishing graphene and boron nitride together. The electrical properties of Graphenide determine the density, power, and strength of the motor coils and inductor windings in the high power systems we need to fling ships around the solar system.

Rotary Transformer

The momentum bank itself is a colossal electrical generator. The flywheel stores energy as rotational inertia but sometimes we need electricity instead. The motor/generator windings at the flywheel/reel interface can generate electricity by slowing one or the other down but we may want to preserve momentum and use only electricity.

The flywheel is 1000 times the mass of the reel so electricity storage in the flywheel can massively outscale the energy storage in the reel. But if they are physically decoupled, how can energy be exchanged on a massive scale?

A simple AC transformer is two solenoids (spiral coils like in the suspension of a car) with the larger coil encompassing the smaller one. Alternating current in one coil will generate a complementary current in the other, without contact and very good efficiency. All energy is stored as DC. Generating a dynamic AC wave will require inversion on a scale only possible with superconducting switching gear. With an AC wave traveling around the flywheel, the reel can induct power wirelessly and use it to accelerate payloads electromagnetically.

If the momentum bank is harvesting energy from the sun or a power plant, the rotary transformer transfers wireless power to the reels so that momentum can be created from other sources of energy.

Energy Storage

Ultracapacitors

Like batteries, capacitors store energy but, unlike batteries, they charge and discharge extremely rapidly making them the essential energy storage system for high power electronics like lasers, particle beams, fusion generators, and other awesome stuff.

Traditional capacitors are limited by how closely the charge planes can be spaced. Atomic layer graphene electrodes can be separated by equally small dielectrics. Capacitive charge planes can be packed at nearly the atomic limit.

Graphene's low resistivity allows rapid cycling with low heat buildup. Laboratory built graphene capacitors already demonstrate energy densities of 1 kWh / m^3, on par with the best batteries but far surpassing their instantaneous power and cycle life.

A capacitor made of interleaved graphene and boron nitride monolayers would have both incredible capacitance and mechanical strength, suitable for the high centrifugal force of the rotating flywheel and reel. The ultracapacitor can even be structural.

The graphenide ultracapacitor is an elliptical annulus (oval donut) wrapped around the circumference of the reel. Its cross section is roughly 10.46 m^2. The MEB circumference is 12,566 m. This equals a volume roughly 131,000 m^3.

Giving it a conservative energy density of 1 kWh / m^3 times a volume of 131,000 m^3 equals a total capacity of roughly **131 megawatt hours**, equivalent to **4.7 x 10^{11} Joules**.

Braking payloads will induce megawatts or gigawatts of transient surges through the ring motors and inductive accelerators. Ultracapacitor arrays are high bandwidth power buffers that absorb these spikes and condition the sudden inrushes and outrushes of energy as the momentum bank converts between kinetic and electrical energy on a massive scale.

Superconducting Magnetic Energy Storage (SMES)

SMES, Superconducting Magnetic Energy Storage systems store energy in toroidal or solenoidal superconducting windings. Superconductor resistance is essentially zero so SMES have near perfect efficiency in both charge and discharge with amazing power density and near zero leakage. They can sink and source huge amounts of power instantaneously, far exceeding even ultracapacitors for our application.

An SMES is a large inductive coil. When electrons flow through the windings it builds up a powerful magnetic field. Without resistance the electron current keeps moving with virtually no decay. When the path to an electrical load is created, the magnetic field begins to collapse, driving energy into the system. Because of the size and number of superconducting windings the MEB will have, the stored energy is immense.

Magnetic Energy Storage Torus (MagneTor)

So now let's design the biggest battery in the known universe. And we shall call it MagneTor! A MagneTor is an orbital scale energy system using the entire circumference of the momentum bank for a superconducting energy storage torus.

Python: MagneTor CalculaTor.ipynb

How much power?

The energy of an inductor in Joules (*E*) equals half the inductance (*L*) in Henries times the current (*I*) squared in Amps:

$$E = \frac{1}{2} L I^2$$

This will tell us the total power in this giant space battery. To populate this equation we need to know the Amperage and the induction. We'll use **300 KiloAmps** of current (*I*). The induction (*L*) is determined by the area of the torus (*A*), the number of windings(*N*), and the permeability of free space (Mu_0) according to this formula:

$$L = \frac{Mu_0 \cdot N^2 \cdot A}{2\pi R}$$

The 'permeability of free space' (Mu_0), also called the magnetic constant, is the resistance to creating a magnetic field. When electrons move they create a magnetic field. This constant links the strength of a field to the amount of current that produces it. The value of (Mu_0) was revised in 2019 to **1.25663706127 x 10^{-6}**.

graphene overwrap calculation take hoop stress of a torus / graphene TS

While that overwrap is thick enough to contain the burst pressure on its own, it too is overwrapped with graphenide ultracapacitor layers. The ultracapacitor is alternating graphene and hexagonal Boron Nitride monolayers. Hexagonal Boron Nitride also has gigapascal tensile strength. So the graphenide ultracapacitor wrapping is structural as well as electrical and defensive as it also plays the major part of our quench defense.

Cryogens

Selecting cryogens comes with some tradeoffs. Each element and molecule has a different freezing and boiling point. Generally, we want the highest boiling point possible and the biggest range between freezing and boiling. We're selecting for existing High Temperature Superconductors (HTSs) but it's likely that better HTSs will be created with even higher critical temperatures. Each improvement reduces the cost and complexity of superconductivity.

Cryogen	Melting Point (K)	Boiling Point (K)	Liquid Range (ΔTL) (K)	Heat Capacity (J/g·K)	Heat of Vaporization (Lv) (J/g)	Notes
Helium	0 at 1 ATM	4.22	(~4.22)	~4.5	20.9	Lowest temp, inert, superfluid. Escape artist, expensive, energy intensive
Hydrogen	13.83	20.27	6.44	~9.7	446	Good thermal properties, light, abundant. Very flammable, embrittles metal, escapes constantly, must be really cold, not practical or necessary with HTSs.
Neon (Ne)	24.56	27.1	2.54	~1.84	84.8	Inert, higher cooling capacity/g than He. Very narrow liquid range, relatively rare/expensive on Earth. Much colder than needed for 100K Tc.
Nitrogen (N_2)	63.15	77.36	14.21	~2.04	199.3	Good thermal properties, decent liquid range, inert, abundant, cheap, mature. Best option if 77K operation is suitable.
Carbon Monoxide (CO)	68.13	81.65	13.52	~2.0	215.5	BP in useful range for 100K Tc. Suffocant, flammable.

Fluorine (F_2)	53.48	85.03	31.55	~1.56	172	BP in useful range for 100K Tc, wide liquid range. Extremely reactive and toxic, powerful oxidizer. Just don't.
Argon (Ar)	83.81	87.3	3.49	~1.09	161.9	Inert, abundant, denser than N_2. Liquid range too narrow.
Oxygen (O_2)	54.36	90.19	35.83	~1.69	213.1	Wide liquid range, good thermals. Highly reactive, strong oxidizer, combusts vigorously.
Methane (CH_4)	90.7	111.67	20.97	~3.43	510.9	Excellent thermals. Flammable. Boiling point too high for existing HTS but potential for future HTSs.
Krypton (Kr)	115.78	119.93	4.15	~0.65	108.1	Inert. Boiling point too high. Narrow liquid range, expensive.

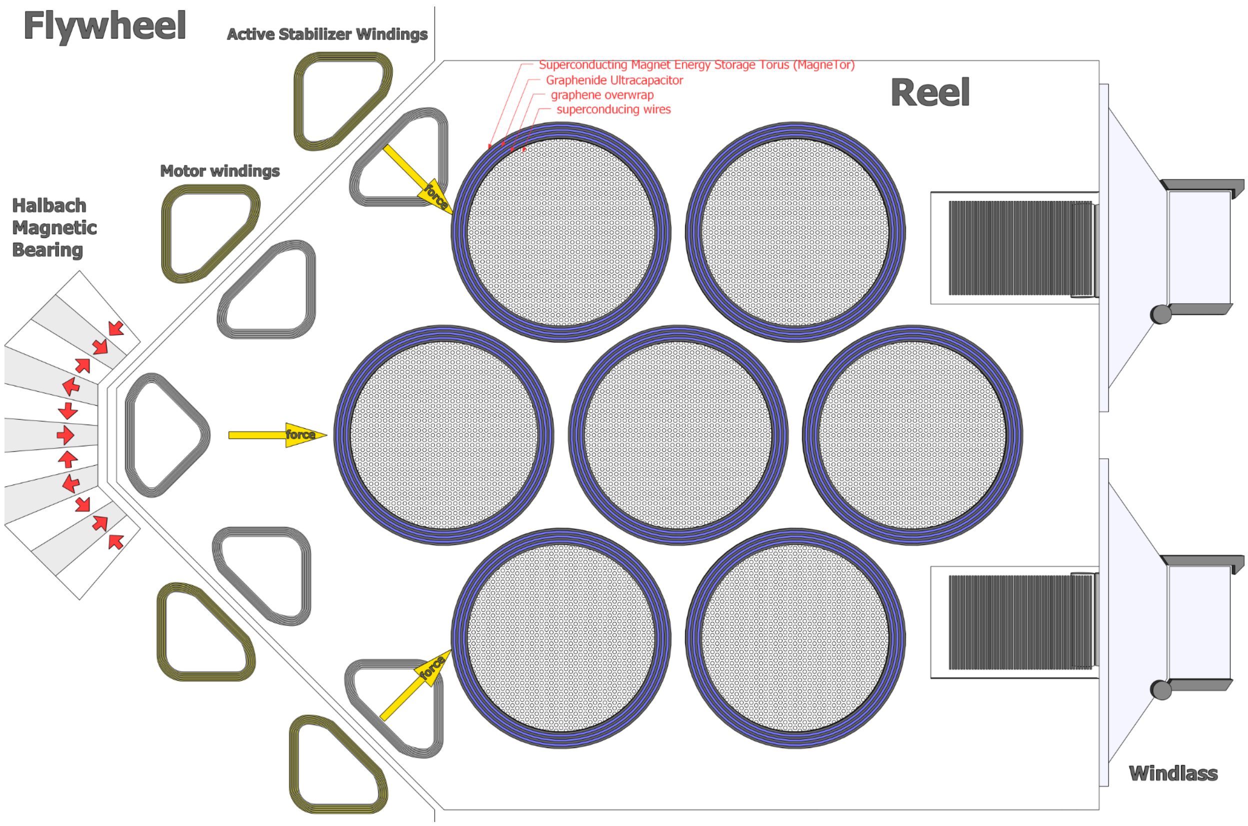
Broadening the scope of potential cryogens gives us some much better options than traditional ones. The high temperature superconductor Yttrium Barium Copper Oxide (YBCO) has a critical temperature, below which a material becomes superconducting, of 77K. This is in the liquid nitrogen range which immensely simplifies the cryogenic cycle compared to liquid helium superconductors.

Maintaining fluids below their critical temperature often requires refrigerants under dangerous pressures and expensive compressors that can operate under high loads and heat exchangers to protect the equipment from cryogenic temperatures. Much of this cost and complexity will be obviated by reasonable improvements in high temperature superconductors. Assuming so we can scale cryogenic systems up to orbital scale and we'll see in the next sections what happens.

Reels

The reels are the vital part of this whirling gadget that exchanges energy between the flywheel and payload. They function like the transmission in a car, applying a differential force on the flywheel necessary to finely control the acceleration rate. The reel positions the windlass at a tangent to the payload. The windlass is a housing for the rollers and accelerators that apply force to the tether. The reel must negate the spin of the flywheel so the windlass can remain stationary relative to the payload.

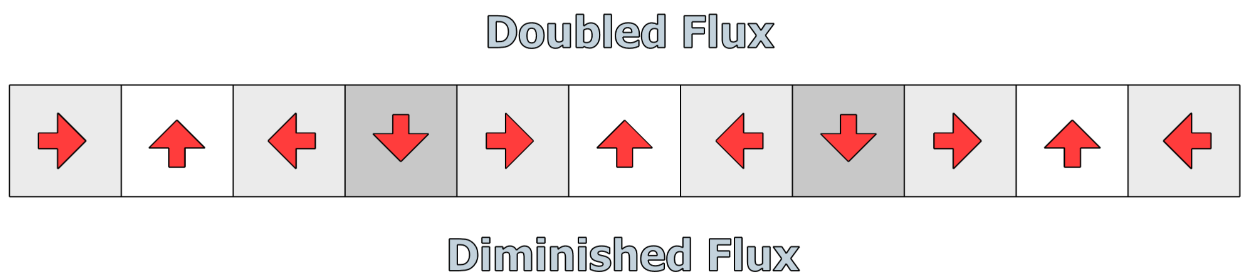
The reels are giant motor/generators that spool the tethers and exchange torque with the flywheel. They ride on magnetic bearings in a V shaped track in the flywheel. The magnets are oriented in a Halbach array. Stator coils around the flywheel and rotor coils around the reel interface stabilize the ring against the tremendous forces exerted during launches and catches.



Halbach Bearings

Mechanical bearings will wear under such tremendous forces and most lubricants will boil in a vacuum so the reel needs to be physically decoupled from the flywheel. Magnetic bearings use magnetic repulsion to levitate a rotating ring electromagnet. Magnetic bearings are already in widespread use for molecular turbopumps, levitated Flywheel Energy Storage (FES) systems, and reaction control wheels on satellites.

Most magnetic bearings use a permanent magnet configuration called a Halbach Array, invented by the physicist Klaus Halbach for use in particle accelerators. This arrangement of the magnetic poles maximizes their force on one side and minimizes it on the other. This results in a doubling of the field strength on the bearing side.



The ring will be subjected to massive radial forces while accelerating payloads. How can we feel confident it will not clip the flywheel while spinning at kilometers per second and turn the whole thing into a 2 exaJoule kinetic bomb? We better have some good margins.

Bearing Force

Let's start by estimating the magnetic field strength of the Halbach array. The field strength of existing neodymium magnets is around 1.2 Teslas. Improved magnetic materials currently under investigation are almost twice as strong. Field shaping optimizations can increase this further. In a Halbach arrangement the field strength is nearly doubled so we'll use a field strength of 2 Teslas in the bearing gap. This should be a very conservative value.

We first need to know the field strength acting on the reel's rotor coils across the gap from the flywheel's Halbach array. Typical motors have a separation less than 1 mm. Our flywheel and reel are both massive and experience tremendous radial and tangential force. For increased safety margin we should increase this gap to 10 cm. The exponential field decay decreases our effective field strength (**B**) at the reel to **1 Tesla**.

This is the force on the passive bearing driven by the static Halbach field. The force can be significantly increased by energizing the coils on the reel to create an active counterfield. It can be magnified tremendously via the Meissner effect by making the rotor coil superconducting with cryogenic cooling. We won't use either of these enhancements in calculating our base case.

To get the bearing's levitation force we want to calculate the magnetic (**P**)ressure in Pascals. The center of the Hallbach array is a meter wide, the wings of the Halbach array are angled 45 degrees and are half a meter long to provide passive axial and tilt stabilization. While the wings will also contribute to the radial repulsion we'll only use the center 1 meter magnet for our calculation.

To determine the pressure we divide field strength (B) squared by two times μ_0 (Mu-zero):

$$P = \frac{B^2}{2 \cdot \mu_0}$$

μ_0 (Mu-zero) is the magnetic permeability of free space. It is equal to $4\pi \cdot 10^{-7}$ H/m (Henries per meter). It converts the magnetic field energy into mechanical force like you feel when trying to force the same poles on magnets together against their will.

Let's sub in our field strength (1 T) on top and $2 \cdot 4\pi \cdot 10^{-7}$ H/m underneath:

$$P = \frac{1^2}{2 \cdot 4\pi \cdot 10^{-7}} \approx \frac{1}{2 \cdot 12.5663706144 \cdot 10^{-7}} \approx$$

$$\frac{1}{25.1327412288 \cdot 10^{-7}} \approx \frac{1}{0.00000251327412288} \approx 397887\ Pa$$

Python: Magnetic Bearing.ipynb

That's 398 kiloPascals, a significant force, equal to **398 kiloNewtons** per square meter. That would be equivalent to around 40 thousand tons of weight on Earth's surface. Meaning, the Halbach array has enough force in a square meter to levitate a semi truck with a full trailer.

The 4km ring has a bearing surface over 12.5km in circumference for an enormous margin. This force is exerted all the way around the ring, levitating and stabilizing the reel. Next we'll see how this handles the force of launching and catching payloads.

Bearing Stability

Launches and catches will subject the MEB to huge off center torques and the bearing must be able to handle them. How much force are we talking about?

We calculated the launch force in GigaNewtons ages ago but it didn't include the tether mass, which we've since established is 47,352,985 kg fully unreeled. We've got to add this to the payload mass of 10,000,000 kg so the combined mass is **57,352,985 kg**. Three g's of acceleration is **29.41995 m/s2**. Force is mass times acceleration:

$$F = 57,352,985\ kg \cdot 29.41995\ m/s2 = 1687321951.05\ N \approx 1.687\ GN$$

Python: Magnetic Bearing.ipynb

1.687 GigaNewtons. This is the maximum force the reel will be subjected to, diminishing with each wrap of the tether. Now, the applied force of the tether is tangential so most of this force will be applied as torque on the reel and only about 5 percent will be radial force acting to crash our reel and delay flights at the spaceport. How much force? 1.687 GN * .5 = **84.366 MN**.

To see if our badass magnetic bearing can handle this we can see what area of the bearing would be required to offset this force. We'll divide that 84 MegaNewton radial force by the counterforce of the the bearing per square meter:

$$Area = \frac{84{,}366{,}097.55\ N}{397{,}887\ N/m^2} \approx 212\ m^2$$

Python: Magnetic Bearing.ipynb

The bearing is 1 meter high so 212 linear meters of bearing will counteract the radial thrust of a launch. The reel is 4000 m in diameter, its circumference is that times pi = 4000 * 3.14159 = **12,566 m^2**. So the repulsion of the passive bearing is more than sufficient.

In addition, the reel and flywheel have supplementary active stabilization coils near the top and bottom of the V channel. Driving high currents through these coils can produce very powerful fields, far exceeding what the Halbach bearing can produce. The passive stabilization alone can handle these forces with an excellent margin, so with all the redundancies on top of that we can confidently fling giant ships all over space.

Ring Mötör

The reels function as electric motors and regenerative brakes. The reels and flywheel can exchange energy bidirectionally. They can exchange motive force or electrical power.

The "stator" and "rotor" are the two parts of a motor that make it go. The stator is generally the stationary part and the rotor rotates within its magnetic field. The flywheel itself is spinning but it has all the mass so it functions as the stator in this assembly.

Applying a current to the flywheel's stator windings generates a magnetic field that accelerates the reel. This can spin the reel in either direction relative to the rotation of the flywheel or the energy can be stored in the SMES as electrical potential. This dynamic coupling turns the MEB into a giant transformer, converting between kinetic and electric energy as necessary.

What force can the flywheel exert to spin up the reel? We can use the formula for a synchronous AC motor where torque (***t***) is equal to the number of coils (***N***) times the magnetic field strength (***B***) times the current (***I***) times the coil area (***A***).

$t = N \cdot B \cdot I \cdot A$

The reel is 12.5 kilometers around and 1 meter wide. There are actually 2 motor rings in the notional design on either side of the Halbach bearing but we'll just do one for now. To get the number of coils we need the coil density around the ring.

Say the winding depth is 10 centimeters. And say we use badass boron nitride jacketed graphene for our wire and these have a diameter of **2mm** including insulation. If the winding face is a meter high that's 1000mm / 2 for **500 turns**. If it's 10 centimeters deep that's 100mm / 2 for **50 turns**. So:

Winding density = winding height · winding depth = 500 · 50 = **25,000 turns per meter**.

The ring is **12,566 meters** around so: 25,000 · 12,566 = **314,150,000 coils**.

That's over 300 million coils in our motor. We could get crazy with it and increase the winding depth to half a meter or a whole meter, this would scale linearly but let's see what we get with just 10cm. Our field strength is **1 Tesla**. We'll just use an arbitrary current of **1 Amp**. And the area is **1 square meter**.

$$t = N \cdot B \cdot I \cdot A = 314,150,000 \cdot 1\,T \cdot 1\,A \cdot 1\,m^2 = 314,150,000\,TAm^2$$

That's 300 MegaTeslaAmpMetersSquared.

There has to be a joke around this composite unit

calculations

The motor has to be able to spin the ring up to 5 km/s to negate the maximum rotation rate of the flywheel and sustain 300 MN at the velocity and regenerate power in reverse.

All motors are also generators so when the rotor rotates without an applied field from the stator it induces a current in the stator which can be stored as electricity. Our motor is ginormous, so the power it generates is too.

Windlass

There are two windlasses rigidly fixed to either side on each reel. The windlasses apply force to the tether and wind and unwind it in concert with the rotating spindle inside the reel. The reel rotates around the flywheel to place the windlass which is pulling the tether at a tangent to the payload. The opposite windlass will reel the tether in.

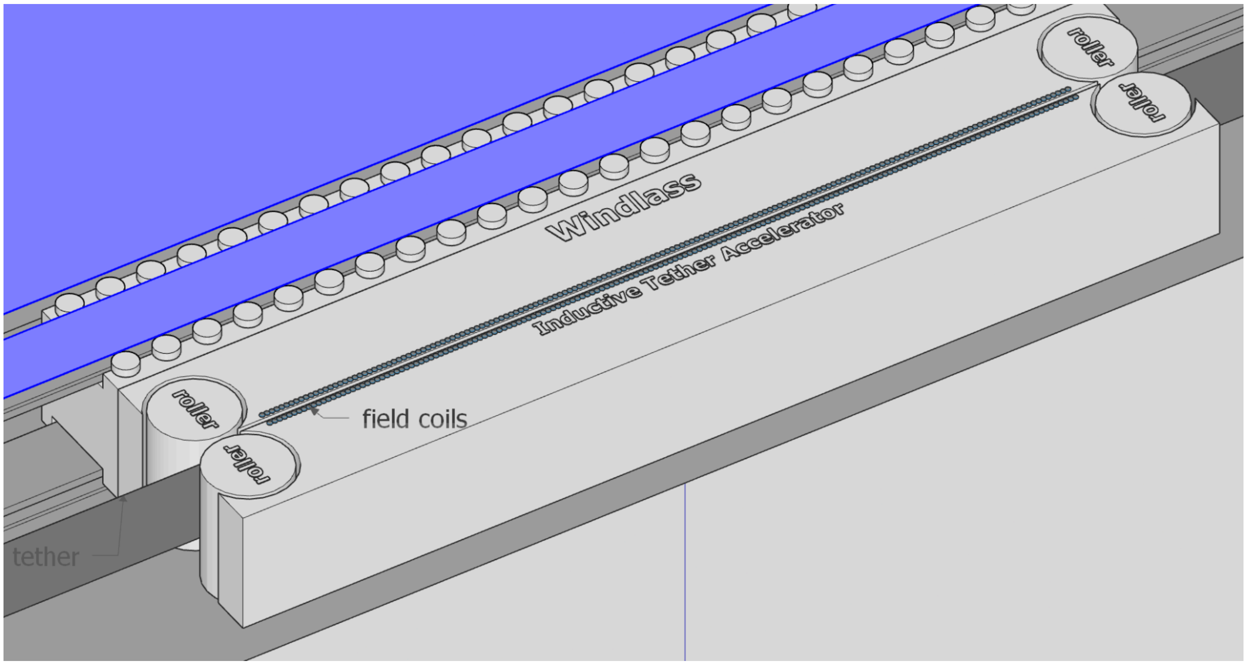
In the first stage of acceleration, the windlass clamps the tether with pairs of mechanical rollers. Powerful electric motors spin the rollers, pulling the tether through and accelerating the payload up to the mechanical stress limit on the rollers, about 7 km/s.

At this point the rollers disengage and the Inductive Tether Accelerator applies a 3 km/s ‘kick stage’ magnetically. The conductive graphene tether is levitated between pairs of balanced field coils on either side and a traveling AC wave pushes on it like a linear motor.

A tether 2000 kilometers long moving 10 km/s exceeds the mechanical stress allowable on the spindle to haul the tether in, so the spooling windlass allows free tether to unspool into open space before applying a sudden jerk on it to create a Mould effect (chain fountain) to deflect the tether away from the accelerator windlass and out of the path of the payload. The spooling windlass can gather the tether in at a safe speed.

As the payload approaches the windlass the tetherhead disengages and the reel rotates the windlass out of the way. The payload is off to its destination but the tetherhead is traveling 10 km/s. The windlass is reoriented at a tangent to the windlass and the tether is drawn taut again and allowed to spool back out under the tetherhead’s momentum while a braking force is applied and a small amount of energy is regenerated. The tetherhead and loose tether are gathered back in and the reel is ready to be used on another payload.

The ITA and rollers work the same way in reverse. When payloads are captured, tremendous energy from their regenerative braking system is dumped back into the MagneTor to be used for accelerating the next payload.



For a reel 12.57 kilometers in circumference, a 1700 km tether would wrap 135ish times and be about 2 meters thick.

Rollers

Rollers are motor driven drums that manage the tether and drive it mechanically. The surface of the length of tether where rollers engage has a microscopic sawtooth texture for the roller to apply high force without slipping.

At very high speeds the velocity of the tether exceeds the winding rate of the spool and the slack is slung into open space or collected by the complementary windlass on the other side of the reel.

Managing the wear and friction of large rapidly rotating wheels and dynamically transmitting torque is one of the greatest challenges of a system like this. The velocity difference between the MEB and the payload could be 10 km/s or higher. The centrifugal force on a 4 km diameter circle would destroy even a reel made of graphene.

This rim speed on a 1m roller drum is over 130,000 RPM. Existing ultracentrifuges have RPMs up to 180,000 but maintaining this rotation rate while applying a significant clamping force will be challenging. So the rollers will be limited to 7 km/s and the remaining acceleration will be done using the contactless inductive tether accelerator.

Inductive Tether Accelerator (ITA)

For very high relative velocities there might not be a reel design which can handle a 10 km/s rotation rate regardless of gear multiplication. Payloads may be inbound at velocities too great for the reels to handle directly. A second stage of contactless accelerators can operate at potentially hundreds of kilometers per second in relative velocity.

Graphene's conductivity means it will generate a reciprocal field in the presence of a strong magnetic field which will repel, rather like maglev trains or electromotive aircraft launchers on aircraft carriers. The MEB's high available power (detailed in later sections) can use the ribbon and electromagnets as a linear induction motor. This contactless acceleration can work in forward or reverse for increasing the acceleration on a payload to far greater velocities than even a sophisticated mechanical reel system can alone.

Because of their linear force application the tether must pass through the accelerator straight so they can only apply force once the ship is on its final alignment. The accelerators will remain disengaged and retracted until the rollers and flywheel have started the pull. Then they will sandwich the tether and energize their field coils.

The ITA is intended to provide the final boost to the outbound payload after the rollers have imparted the 7 km/s. How much energy will this require?

The payload weighs 10 kilotons: **10^7 kg**

3 gees of acceleration is **29.43 m/s^2**

Force is mass times acceleration:

$$F = 10^7\, kg \cdot 29.43\, m/s^2 \approx 294.3\, MegaNewtons$$

The ITA needs to apply a constant force of **294.3 MN** for the duration of the pull. How much energy does the ITA require to exert this force? We need to determine the electric current required to generate this acceleration

The time it takes to accelerate from one velocity to another is the final velocity (**10,000 m/s**) minus the starting velocity (**7,000 m/s**) divided by the acceleration rate (29.43 m/s^2).

$$t = \frac{10000\, m/s - 7000\, m/s}{29.43\, m/s^2} = \frac{3000\, m/s}{29.43\, m/s^2} \approx 101.94\, s$$

To get the power bill for that we need to figure out how long it must apply that force to accelerate the payload by 3 km/s.

Tetherheads

Ships and cargoes would have to be designed with this mechanism of transportation in mind. The structure of the ship must be able to sustain certain G loads in tension for minutes to hours. There must be a latch and release mechanism to attach to the ships. There must be a vectoring and thrusting mechanism to align it. I call this the 'Tetherhead', which has a latching mechanism for grabbing onto reinforced tow points on ships or cargo containers which distributes the force.

Once a tetherhead has clamped the payload, the tether becomes a leader line other tetherheads can ride on to make their attachment, or they can exert a direct force on the tether without even touching the tether or payload by applying a Lorenz acceleration on the tether with its inductive tether accelerator.

Tetherheads provide teaming mechanisms to allow multiple MEBs to work together or stage launches. Imagine, for a moment, 10 momentum banks in a line spaced out by 1000 kms each. As the ship nears the 1st MEB, the 2nd latches it and the 1st disengages. The 2nd MEB continues the acceleration while the 3rd connects as the reel runs out on the 2nd MEB. The process continues with handoffs so that a total acceleration ramp of 10,000 kms is achieved but no individual tether needs to be longer than 1000 kilometers.

Imagine further that the MEBs are staged and paired so that two momentum banks are attached to the tether head. They can double the acceleration on the ship or divide the force between them. More momentum banks combining their tethers would mean individual graphene ribbons could be thinner, longer, and lighter.

If the tetherhead is what actually attaches to the ship, why is it being described last? I needed you to read that bit on linear accelerators first because the most performant version of this system is not a grabby clamper at the end of a rope. It is a magnetic climber that shuttles

The tetherhead carries a very light, thin leader line to make the initial connection to the payload. The heavy and massive acceleration tethers ride down the leader line to engage the anchor head. The leader line disengages and reels back in to snag its next payload.

Interstellar Travel

Solar Orbiting Interstellar Stages

Solar Orbiting Stages take advantage of 2 important features of the sun. It's hot and it's very heavy. A ring of evenly spaced momentum banks in a highly elliptical solar orbit aligned with a destination star can use these properties of the sun to assist interstellar payloads up to a fraction of light speed.

As an MEB is approaching its solar periapsis it is at its highest velocity relative to the Sun and receiving its maximum solar irradiance. The departing ship matches the orbit of the interstellar momentum banks and begins a precisely timed series of the accelerations from one bank to the next, each adding more velocity, while the ship is descending into the sun's gravity well.

The ship receives dozens of accelerations in combination with the Oberth Effect: a gravitational slingshot. The last momentum bank is near periapsis, itself traveling near its maximum velocity. It provides the last kick to the starship, flinging it away from the sun. The starship uses its engines and solar sails to accelerate away

how many stages to reach 3000 km/s?

10000 with light sails?

how long to Alpha Centauri?

This is python script output calculating a large mass ship (500 kilotons! (>aircraft carrier)) using very long tethers and 48 combined MEBs to reach 78 km/s. Which is about .026% of light speed. With staging I think higher numbers are possible. A ship of that mass could have additional propulsion methods including nuclear engines, and a light sail for combined technologies to reach higher speeds.

Enter tether length: 200000 km

Enter tether width in meters (m): 10

Enter tether thickness in meters (m): .001

Enter safety factor (ex .5 for 50% of maximum tensile strength, 1 for no safety factor): .5

Enter the number of combined tethers for multiple MEBs: 48

Enter the ship mass in tons: 500000

Enter acceleration in m/s^2 or specify g (ex '20' or '1.6 g'): 4 g

Tether length: 200000000.00 m

Tether strength: 31200000000.00 Pascals

Ship mass: 500000 tons

Acceleration (m/s^2): 39.23

tether mass: 4540000 tons

Combined mass of tether + ship: 5040000 tons

Calculating final velocity:

Warning: Desired acceleration exceeds tether strength. Using maximum acceleration: 6.19, 0.6313 g.

Acceleration will increase up to the desired acceleration as the deployed length of tether is reduced.

Ran out of tether in 7270 seconds, (2.02 hours) going 78092.90 meters per second

Final acceleration rate was 39.29 m/s^2 (4.01 g)

Failure Modes

Catastrophic Failure

tether breaks and collisions

ring or flywheel disintegration

Misses

We can’t have ships flying off into interstellar space, staged deceleration with teams and multiple MEBs, ships with passengers carry a minimum amount of fuel to circularize an orbit, so it might result in a 5 month elliptical with a second capture attempt.

It should be required for passenger ships to pass through a MEB gateway where the interplanetary velocity will be absorbed. That way the ship is always captured into orbit of the destination planet and missing the orbital MEB won’t result in the ship flying off into deep space and everyone dying. It does mean the trip might get extended by weeks or months and everybody will have to get to know each other better. So passenger ships will probably need emergency rations, facilities, and a few km/s in delta v.

This can also be mitigated with some exotic orbital maneuvers; if, for example, a ship misses the gateway and the velocity difference is too great, an MEB can launch a bolo mass into the runaway ship’s trajectory. This could be a fuel tank with a simple reel, tether, and tetherhead. The fuel tank will function as a tiny MEB and grapple the ship. This alone might be enough to slow the ship into a closed orbit. After capturing the fuel tank, it can reel it in, refuel, and change course.

Weaponization

PetaJoules of energy in any form are weaponizable.

describe KE weapons and relate to comet impacts

MagneTor Catastrophic Discharge

The superconducting graphenide has such astounding temperature stability and charge density we should refer to it as Clark conductors. But something really really bad can happen when Clark conductors unexpectedly become Kent conductors.

This could be a single hot spot where a part of the loop stops superconducting because of a wire defect or a hot pocket where the cryogen starts boiling or maybe Dave, the middle manager, saw that liquid argon is way cheaper than neon so he cut a few corners to hit those quarterly numbers in time for his review and got that promotion. So Dave moved over to the corporate office on Luna and things are fine until we try to catch a big passenger ship full of orphans and juice MegaAmps of current into the MagneTor and 'BLAMO!' is what the headlines say because there's not much sound in space. Dave will give interviews explaining how he is personally overseeing an investigation into the source of the accident and his thoughts and prayers are with those poor orphans.

Poof

When you're storing PetaJoules of energy and any part of your loop stops superconducting the resistance heating is instantaneous and catastrophic. Nonsuperconducting graphene still has a very low resistance and a very high sublimation point so I wish it could just tank that fire spell but no, when the juice gets loose it will flash into atomic carbon along with everything around it.

This will likely destroy the reel ring, and probably the outer layers of the flywheel. With a rim speed of 6 km/s and gigatons of mass, the flywheel will send kilotons of graphene and steel flying in every direction at orbital velocity.

It would make a great plot for a movie where there's only hours to restore the cryogenic loop before it kablams and rains hypervelocity diamonds down on Earth or Mars or wherever. If it can't be stopped or it happens suddenly there needs to be a way to rapidly discharge the MagneTor without kablamization.

Zap

Adding to the trouble. This would also release a massive EMP. A quenched 100 PetaJoule superconducting ring 4 kilometers wide would release exawatts of radiated energy.

These waves would couple strongly with long conductive things like power lines and pipelines. Powerful transients would propagate across the power grid, exploding transformers, phone chargers, clock towers, magic smoke everywhere.

Discharge

So, with great power comes great responsibility. How do we harness petaJoules without looking like petaFools? Easy, we have to waste it before it wastes us.

In a catastrophe we have to discharge an orbital scale inductor in milliseconds or it will fry every iPhone on Earth. And the moon probably. While the extra margin built into the MagneTor's design should prevent this catastrophe from ever happening, we should add some safety features in case it does.

Depending on the state of charge and the suddenness of the quench the problem can be isolated. Just in case, we need the ability to slow down and break up the release of energy to minimize the amplitude of pulse created and save the planet from a Mad Max descent into carbureted vehicular madness.

Voltage, current, and temperature sensors around the loop connect to control logic that monitors changes. This control system would be constantly monitoring and identifying issues before any part of the torus quenches.

The following table lays out the quench emergency operations.

System	Energy Absorption Capacity	Response Time	Primary Function	Notes
Voltage/Temp Sensors + Relay Logic	N/A (detection only)	<1 ms	Early detection + automated dump initiation	Needed for all other mitigations
Solid-State Dump Switches	Full loop (0.1–1 PJ)	<1 ms	Redirect current to resistive loads or ultracaps	Assumes high-speed optoelectronic relays
Internal Dump Resistors (Graphene Body)	~1 PJ (per loop)	1–2 ms	Converts current to heat in structural mass	Depends on reel thermal limits
Graphenide Ultracapacitor Wrap	~0.1–1 PJ (10–100x buffering)	<1 ms	Electrostatic absorption of energy spike	Limited by charge rate and field strength
Cryogen Ejector Slugs	~10–100 GJ per slug	5–10 ms (mechanical trigger)	Thermal absorption and mechanical interruption	Multiple slugs per loop scale to >1 PJ
Inductive Catch Loops	~100 GJ–1 PJ per loop	Passive (instant)	Inductive coupling to bleed field collapse into heat	Limited by loop size and coupling factor
Phase Desync / Eddy Current Brake	~0.1–1 PJ	1–5 ms	Converts stored momentum into resistive heating	Also slows flywheel as bonus

Blanket Quench (Controlled Collapse)	Up to full system (100 PJ)	5–10 ms trigger	Uniform field shutdown to prevent lopsided failure	Needs cooling & huge dissipation margin
Shaped Explosion (Reel Sacrifice)	Up to full system (100 PJ)	5–20 ms (mechanical + trigger logic)	Final failsafe; spatially directs field & debris	Direct the explosion and impulse away from Earth.

add up discharge and determine conversions, does the heat melt everything? Can the structural ultracap absorb enough?

Handwavium

This work is somewhere between hard scifi and speculative engineering. Hard scifi is a subgenre of scifi that emphasizes scientific rigor, realism, and cleverly hiding technical details in a story such that the reader doesn't know they're being educated yet finds themself inexplicably identifying the ingredients for thermite at the hardware store.

There are 3 cardinal sins of scifi: unobtainium, technobabble, and handwavium. And there are levels of these sins just as there are circles of hell for the lazy writers that commit them.

Unobtanium is a material with unrealistic or downright impossible properties that doesn't and probably could never exist in our universe. Or it might exist (like neutronium) but you'll never get any. Flawless macroscale graphene might prove to be unobtainium but I think it's doable or I wouldn't have spent all the time on this when I could have been playing video games.

Technobabble is basically what you get if you really want something cool and sciency but instead of spending the time reading Wikipedia and endless reference material and then watching boring, poorly recorded youtube videos you instead channel Deepak Chopra and just say that it resonates with quantum superpositions of infinite potentiality.

Your casual readers might never know the darkness you've summoned. But I'll know. And the nonlocality of my disapproval is so great it will cause a slow leak in your car tire. Only Geordi La Forge has the wisdom to safely engage with the forces of antipolarized technobabble. So if you ever hear the words 'quantum' or 'vibration' from someone without tape on their glasses then hide in the nearest refrigerator until the danger has passed.

I think the only crime I'll have to answer for is 2nd degree handwaving, a type of sloth whereby a hard working and underpaid yet very charming writer just doesn't have the time to solve every damned detail. That's basically a misdemeanor. There are, of course, cruel and arbitrary applications of handwavium that even good people have perpetrated.

Dilithium crystals, warp drive, Epstein Drives and so forth just kind of shrug at the impossibility of faster than light or propellantless space travel (except for mine of course) and jump, fold, hyperspace, or jazz hands their way out of it. If you want to explore brave new worlds with the same crew each episode then it's something we have to tolerate for the sake of a good story.

Light sabers are a great example of pure handwavium. Why do they stop at like 1 meter? How do they cut through metal beams but not each other? It's handwavium and it's fine. The force is too. The audience accepts these rules as internally consistent within the Star Wars universe. The problem was actually when they tried to substitute technobabble for handwavium with all that "midichlorians" bullshit and now nobody is happy. Unobtainium from Avatar somehow manages to be all three at once. You break-a my heart, James Cameron!

All that to say, if you find any serious omissions please let me know.

In my defense, there are some things I've chosen to skip because they are, in my opinion, very solvable, just not by me, at least in a reasonable amount of time. This paper was supposed to be a few pages. Here we are, 50 pages in.

I feel like a jerk but I'm not going to solve the control, feedback, or coordination systems rn. Let's just sprinkle some AI on that and call it done.

When a nonrigid tether is under acceleration and under tension it will tend to oscillate at some frequency relative to its length which means the anchor points will experience yanking, whipping, and spanking forces. These can be canceled out with a bit of harmonic counteroscillitory retroencabulation.

About the Author

Galen Matson is a rogue engineer. On average, he lives in America. His cat's name is Paxton.

2025-06-19

Send praise or condemnation to: galen.matson@gmail.com

Acknowledgements

Original Geniuses: Robert L. Forward, Hans Moravec, Robert Hoyt, Kirk Sorensen, Robert Heinlein, Kim Stanley Robinson, Gerard K. O'Neill, Arthur C. Clarke, Winchell Chung, Isaac Arthur, Carl Sagan, Anthony Weir, the creators of BATTLETECH, the writers of The Expanse, and everyone else that writes or supports visionary space, hard scifi, and hard engineering.

The teams at OpenAI and DeepMind. Not a single sentence of this paper was written by AI. Otherwise it would be a much better paper. ChatGPT and Gemini were vital in exploring these concepts, coming up with equations, and finding the most current science and research.

My homies: Somia, Christian, James, and everyone that listened to me rant and gesticulate while I thought this through.

Confessions

I failed high school math. I live in a van. I write hard scifi. It's not published because I never finish anyt