Aim Is All You Need

A Speculative White Paper On Externally Pulsed Propulsion

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Abstract

In 2017, Google Research published *Attention Is All You Need* [54]. Their paper introduced the Transformer, which let neural networks capture long range dependencies. Just a few years later, OpenAI developed tools like ChatGPT [39] that resemble hypothetical early prototypes of the computers in Star Trek [49].

But here's the bittersweet truth: While our screens flicker with progress, the tangible realms of space, energy, and paleontology remain comparatively stagnant.

Dude, Where's My Spaceship?

This paper's goal is to enable our progress in physical realms to catch up with our progress online. Our journey requires applying a single unifying idea that is much simpler than attention - aim.

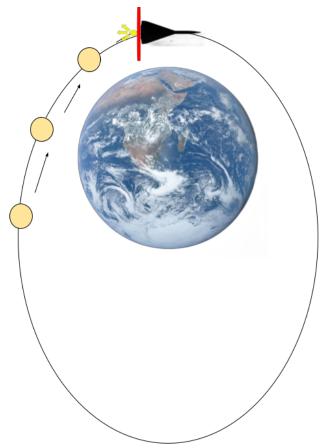

Figure 1: PuffSats from a first rocket (not shown) crash into a second target rocket and provide propulsion. [57]

Consider a "PuffSat" – a specialized device whose mass is mostly a low density gas. The PuffSat can generate gas on demand explosively, via sublimation, or by pre-inflating like a PuffSat. The PuffSat can perform small navigation adjustments using ultra lightweight microthrusters and electronics.

Now, envision a scenario with two rockets. The first rocket deploys a series of these fast moving PuffSats. As shown in Figure 1, the deployed PuffSats precisely follow a path to sequentially inflate and impact a shock absorbing momentum pusher plate on a separate target rocket. These collisions deliver high density jolts of pulsed energy and momentum to the target vehicle, enabling a surprisingly broad range of groundbreaking applications (See Table 1).

Paralleling their role in consumer AI, neural networks offer a promising avenue to extend current CubeSat formation flying algorithms with the precise control required for this externally pulsed propulsion.

This speculative white paper is a brainstorming exploration that could be followed by more rigorous analysis. If the ideas prove too advanced for near term implementation, they can instead serve as fodder for hard science fiction. The paper summarizes and updates some of the writings from the author's own blog, "Aim Is All You Need."[45]

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1 Introduction

Conceived in the 1950s and later popularized by *The Three-Body Problem* [27], Project Orion remains one of the most compelling rockets ever proposed. It uniquely offers specific impulses surpassing those of electric propulsion while delivering thrust levels on par with chemical rockets [62]. Orion would propel a spacecraft by directing hypervelocity plasma from nuclear explosions onto a pusher plate. Despite its theoretical promise, Orion faced insurmountable challenges related to political feasibility, radioactive fallout, and the impractical mass requirements stemming from the high minimum yield of nuclear explosions. Nevertheless, Orion conceptually validated the physics of hypervelocity pulsed propulsion.

Table 1: A checklist of grand challenges externally pulsed propulsion can solve

Safer Satellite Launch	We'll launch expensive satellites and astronauts without strapping them to fragile extremely high propellant mass fraction rockets. See subsection 3.1.
Suborbital Transit	We'll create a viable suborbital travel vehicle allowing passengers to take off from normal airport runways and reach anywhere in the world in less than 2 hours. Noise pollution near population centers will be no worse than it is with conventional aircraft. See subsection 3.2.
Rocket Revolution	We'll end the tyranny of the rocket equation. We'll still use small rockets, but giant rockets with high propellant mass fraction will no longer be needed to reach orbit. See subsection 5.1
Lunar Lift-off	Launching from the moon may still require volatiles, but not the more difficult task of making and storing high performance rocket fuel. See subsection 4.2
Jurassic Dark	As a side effect of our advances, we'll create the field of lunar cold trap paleontology and discover concrete evidence for how life originated on Earth. We'll build a genetic record of extinct species from ancient geological periods, like the dinosaurs. See subsection 4.4
Straw Ways To Heaven	We can construct terrestrial megastructures, extending from the ground to the edge of space, without relying on advanced magnetic technologies such as Lofstrom Launch Loops [22]. A particularly ambitious yet beneficial example might be a vacuum tube connecting Earth and space, a "Straw Way to Heaven." See subsection 6.1.
Carbon Cancelled	We will solve our energy problems with carbon negative fuel that absorbs the carbon dioxide produced by industry, all while using minimal land and resources. See subsection 6.6.
Moon Mining	We'll develop in-situ resource utilization (ISRU) technology, first on our moon (See subsection 4.3) and then on icy moons like Saturn's moon Phoebe (See section 7)
Cosmic Commutes	We'll build fusion powered spaceships with Earth-like gravity that travel on brachistochrone trajectories with constant acceleration and deceleration between destinations. subsection 6.7

Our approach replaces nuclear bombs with precisely aimed, hypervelocity gas puffs sequentially impacting a rocket's pusher plate. These gas puffs can be downscaled to practical sizes. Unlike nuclear explosions, small hypervelocity gas impacts could be efficiently contained within a pulsed propulsion chamber.

Leveraging gravity assists and the Oberth effect [61], hypervelocity PuffSats impacts could achieve high energy densities and specific impulses. Recent CubeSat formation flying and neural network advancements make the extremely precise navigation for this externally pulsed propulsion viable.

This speculative white paper presents a preliminary back of the envelope analysis of what are clearly very ambitious ideas. While rigorous, high fidelity modeling is left for future work, our aim is to stimulate fresh thinking and new research directions. Whether this concept remains a provocative thought experiment, inspires science fiction, or evolves into a transformative 21st-century technology, it underscores bold and novel applications of emerging formation flying capabilities.

2 Groundwork And Prior Work For Externally Pulsed Propulsion

2.1 Navigation For Externally Pulsed Propulsion

Millimeter accuracy CubeSat formation flying is rapidly advancing. The European Space Agency's (ESA) Proba-3 mission recently demonstrated this capability by creating artificial solar eclipses with a precise two satellite formation [13]. The Stanford Space Rendezvous Laboratory's VISORS mission, nearing flight readiness (as of June 2025), will further showcase precise formation flying with CubeSat sized craft [15].

Our hypervelocity PuffSats employ formation flying algorithms for precise positioning. Unlike Proba-3 and VISORS, our formation lasts a single orbit. This means our PuffSat microthrusters face less demanding fuel efficiency requirements.

To maximize the gas mass and minimize the solid mass of mini-thrusters and electronics, a few coordinator satellites with enhanced computing power will measure the PuffSats' positions and relay adjustment instructions. As shown in Figure 2, these heavier coordinator nodes fly along with the PuffSats but don't impact the target rocket. We keep the electronics on the PuffSats as simple and low mass as possible. Given that thousands of PuffSats are needed per mission, mass production will reduce costs.

Each PuffSat carries perhaps 100 grams of solid mass, including sensors, power systems, microthrusters, and low-bandwidth communication links to the coordinator nodes. To prevent this mass from impacting the rocket, we propose several disposal strategies

- **Active Elimination:** Equipment on the target rocket could vaporize the solids via electric discharges, directed energy beams, or sprays of material that hit the incoming PuffSat solids before pusher plate impact.
- **Passive Routing:** The solid components could pass harmlessly through a small aperture in the pusher plate.
- **Discard Before Impact:** The solid components could launch slightly away from the rocket just before impact.

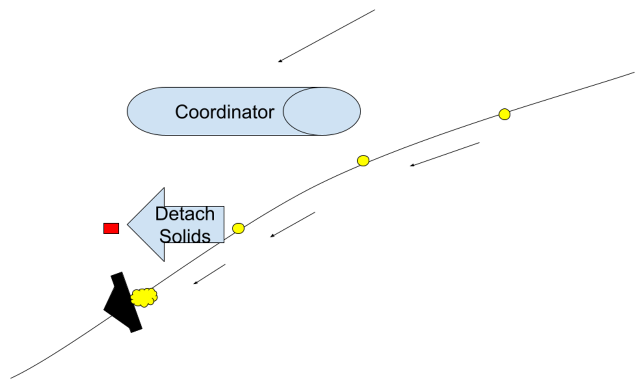


Figure 2: Coordinator nodes that do not impact the spacecraft handle more complex measurement and computation. PuffSat solids can detach before spacecraft impact, or fly through a small aperture in the plate.

Instead of relying on solid components, radiation pressure could directly manipulate PuffSats. Coordinator nodes might employ kilowatt-class lasers to adjust PuffSat trajectories. The intense laser light could also induce temporary thermal or photochromic changes in the PuffSat's skin, altering its shape or color. If these changes briefly persist, the altered solar radiation pressure would magnify PuffSat trajectory changes compared to the laser's radiation pressure alone. Eliminating solid components on PuffSats reduces the risk of pusher plate damage in an accident. The PuffSats cost less if they don't include microthrusters and electronics. However, space lasers present several drawbacks compared to microthrusters. They exert weak forces on the PuffSats, demand substantial power sources for coordinator nodes, and are not yet a fully mature technology.

Equipped with a high performance rocket based reaction control system, the target craft precisely adjusts its trajectory to intercept each PuffSat in the formation. To achieve the required millimeter scale precision, we use an Unscented Kalman Filter (UKF) [55] to estimate each PuffSat's position and velocity under the nonlinear dynamics of orbital motion. The UKF is well suited to systems with known dynamics and Gaussian noise, as it efficiently propagates uncertainty through nonlinear models. In this context, the large number of PuffSats provides a dense stream of relative measurements, which improves filter accuracy. However, UKF performance can degrade in the presence of unmodeled perturbations, non Gaussian noise, or intermittent sensor dropout. Those conditions are frequently encountered in low Earth orbit.

To mitigate these challenges, we augment the UKF with a neural network based estimator such as KalmanNet [43], which learns to correct residual errors and adapt to anomalies in the measurement stream. Neural algorithms implicitly model noise, dynamics, and sensor behavior from both simulated and real orbit data, enabling robust estimation even when classical assumptions fail. This hybrid approach enables robust state estimation across diverse orbital scenarios, supporting precise trajectory control and reliable PuffSat interception.

After each PuffSat impacts the rocket, we'll need to rapidly adjust for any disparities between predicted and measured propulsion. This requires quickly solving for the necessary thrust adjustments to intercept the next PuffSat, all while adhering to the constraints on our rocket's performance. With thousands of PuffSats, the rocket's system must also be robust to occasional PuffSat failures caused by micrometeorite impacts or manufacturing defects. Neural networks show significant promise here because they can provide controllers with accurate initial guesses for trajectories [16] and constraints [3]. These good initial guesses produce fast convergence without compromising control guarantees. Additionally, reinforcement learning shows promise for developing fast space trajectory recovery algorithms for anomalies like lost PuffSats [68]. This powerful combination of neural networks for rapid rocket adjustments and accurate formation flying can effectively keep the rocket on course for the next PuffSat interception.

2.2 Comparison To Pellet Beam Propulsion Prior Art

In 2001, Gerald Nordley proposed an externally pulsed propulsion system in which hypervelocity pellets, capable of self steering, transfer momentum to a spacecraft via impact with a pusher plate [38]. This concept built upon earlier work by Clifford Singer [47], who envisioned unguided macroscopic projectiles launched at extreme velocities.

Both Singer's and Nordley's designs relied on mass drivers. These devices would need to accelerate sizable objects to very high speeds, posing formidable engineering challenges. To address this, Jordan Kare introduced the SailBeam concept [19], which replaced the mass driver with solar or laser driven miniature sails. Kare further proposed vaporizing the sails upon impact and using a magnetic pusher plate to convert the resulting plasma into thrust.

These pellet stream propulsion ideas often prioritized interstellar speeds over economic feasibility. Instead of using expensive mass drivers or light sails, our PuffSat pulse propulsion system focuses on achieving high speeds primarily through low cost orbital maneuvers. Our PuffSats can weigh kilograms, and are mostly comprised of environmentally benign gases like water vapor. This means they generate substantially less pollution for a given ΔV (delta-v), which makes them practical for very large scale near-Earth applications.

Although our PuffSats contain electronics, the majority of their mass consists of inexpensive gases. This composition enables comparable propulsion at significantly lower cost than systems dominated by electronics or solar sail material. Water is also abundant and mineable throughout the solar system. Larger PuffSats can afford heavier electronics than Nordley's snowflake sized guided pellets. While PuffSats could, in principle, interact with magnetic pusher plates, their largely gaseous composition may make direct kinetic impact a simpler and more robust mechanism for momentum transfer. The vaporization of mostly gaseous PuffSat material on impact is also more straightforward than for solid pellets.

2.3 Mass Fraction Of Rocket To PuffSat Mass

For externally pulsed propulsion to be a viable option, the ratio of PuffSat propulsion mass to rocket mass must be low for relevant rocket velocity changes. We develop a closed-form approximation for this ratio (Equation 7 in Appendix A). Since real collisions are not perfectly elastic, our approximation includes an energy loss "fudge factor," e. Justification for a high e comes from Project Orion's findings [17]. The Orion team found that pusher plate collisions could be opaque. This opacity implied minimal kinetic energy loss to pusher plate heating, resulting in a more elastic impact. Pusher plate durability and opacity could be further enhanced by spraying a thin layer of oil on the plate between impacts. Additionally, a curved, roughly parabolic pusher plate would produce a highly collimated gas reflection. Therefore, we select a high $e = 0.8$.

Relevant mass ratios and mission scenarios are summarized in Table 2. This table clearly shows that externally pulsed propulsion can lift significant mass into orbit. For instance, if a reusable rocket like SpaceX Starship [48] lifts $25\,\mathrm{t}$ of PuffSats into a trans-lunar orbit, they can propel a $32\,\mathrm{t}$ target craft into low Earth orbit. This exceeds the Space Shuttle's maximum capacity [63] or the zero fuel mass of smaller regional jets like the Embraer E170 [59].

2.4 Handling Space Debris

The solid components of each PuffSat risk becoming space debris. To avoid this, we can intercept the PuffSats prior to their orbital periapsis. For example, a PuffSat interception at a $200\,\mathrm{km}$ altitude likely follows a predictable trajectory with negligible atmospheric drag. If the PuffSat periapsis is near $100\,\mathrm{km}$, this likely deorbits any solid components. They ideally then burn up or fall over remote oceans. Two other techniques prevent long lasting space debris:

- The J2 perturbation induces a changing argument of periapsis. Any PuffSat orbit designed to avoid specific critical angles will eventually have a periapsis over the equator. Since the Earth is wider at the equator, periapsis will be at a lower atmospheric altitude with much more drag.
- If our PuffSat interceptions occur at night, subsequent daytime periapsis will be over a warmer atmosphere with higher drag at the same altitude.

2.5 PuffSat Deployment Details For Low Earth Orbit Scenario

Let's consider the complexities of launching target rockets into Low Earth Orbit (LEO) with propulsion from PuffSats deployed in highly eccentric Earth orbits.

It's crucial to acknowledge that these PuffSats will not follow strictly identical Keplerian orbits. As the target rocket accelerates, the optimal PuffSat interception point moves along with it, so that successive PuffSats have slightly different

Table 2: Mass ratio of rocket to PuffSat with fudge factor $e = 0.8$ [20]

Rocket Final Velocity $(\mathrm{km/s})$	**PuffSat Velocity** $(\mathrm{km/s})$	**Rocket Initial Velocity** $(\mathrm{km/s})$	**Rocket/PuffSat Mass Ratio**	**Scenario**
7.784	10.916	0	1.28	Eccentric PuffSats with apogee at lunar distance pushes rocket to minimal low Earth orbit. See subsection 3.2
0	-7.784	7.784	2.308	Decelerate intercity rocket for powered reentry with retrograde PuffSats in low orbit. See subsection 3.2
0	-10.916	7.784	2.97	Decelerate intercity rocket for powered reentry with retrograde PuffSats from lunar orbit. See subsection 3.2
23.66	69.272	0	3.83	PuffSats approach Earth from Jupiter retrograde Hohmann trajectory and push the object to escape velocity and then to a periapsis near Parker Space probe. See subsection 5.5
40.17	69.272	0	1.85	PuffSats approach Earth from Jupiter retrograde Hohmann trajectory and push the object to escape velocity and then to a periapsis near Parker Space probe but in a retrograde orbit around the Sun. See subsection 5.5
10.916	69.272	0	9.331	PuffSats approach Earth from Jupiter and push a rocket into an elliptical orbit. See subsection 5.6
3 and 3.7	7.20	0	1.455	Launch PuffSats from the moon to trans-lunar injection orbit with low periapsis on Earth. See subsection 4.2
0	-2.38	2.38	2.30	Decelerate trans-lunar payloads to land on the moon, ignoring the moon's speed around Earth. See subsection 5.1
24.98	35.25	0	1.29	PuffSats approach Saturn from Phoebe and push a Helium-3 payload into a temporary very low orbit around Saturn. See subsection 7.1

orbital elements. For low-density PuffSats, solar radiation pressure will significantly distort their orbits. To simplify orbit planning and maintain consistent effects across the fleet, it's ideal for each PuffSat to remain outside the shadow of the others. This may necessitate slight variations in orbital parameters, such as inclination, for nearby PuffSats. The micro thrusters on each PuffSat make corrections for unmodelled perturbations. We still ensure each PuffSat achieves the correct interception position with the target rocket.

Fortunately, strategically deploying our PuffSats near apoapsis can minimize the ΔV required for these inclination changes. Apoapsis PuffSat deployment also minimizes the ΔV for appropriate PuffSat spacing. The small ΔV changes required at apoapsis should enable practical designs for a very precise mechanical PuffSat launcher onboard our PuffSat deployment rocket.

3 To The Moon by Smart Gas Balloon: The Business Case For Externally Pulsed Propulsion

3.1 Making Starship's Excess Capacity Useful To Satellite Customers

SpaceX's Starship may be the first fully reusable rocket. At scale, this could dramatically reduce space flight costs. However, the rocket's large payload size is probably too big for today's space industry needs. For example, in *The New York Times*

> Carissa Christensen, the chief executive of Bryce Tech, an analytics firm that tracks the launch market, says launching Starship frequently will be key to closing SpaceX's business case, but finding customers to fill the rocket's giant payload capacity will be challenging. "Starship's payload capacity is huge; it's very, very big, and there aren't that many commercial uses today for a rocket that big," she said. "Maybe it'll be so cheap that it makes sense to launch satellites on it if it's not full or near full." [18]

Although many satellites might be too small to fill up Starship, they can still be very expensive to build and test. For an extreme example, the James Webb Telescope [37] cost $9.7 billion dollars [5] to build. *McKinsey Consulting* argues

> Safety and reliability will continue to be overarching concerns, suggesting excellent execution will be table stakes for a competitive launch company. [9]

Once rockets start ferrying astronauts, reliability becomes even more emphatically non-negotiable. Fully stacked, Starship weighs $5\,\mathrm{kt}$ at launch [48], yet its empty mass is only $300\,\mathrm{t}$. That's an awfully thin soda can strapped to a $5\,\mathrm{kt}$ bomb that we're entrusting with billion-dollar satellites or human passengers.

By contrast, a suborbital rocket that merely reaches $200\,\mathrm{km}$ in altitude might have a propellant mass fraction under 50 percent. This greater structural margin allows for more robust, reliable engines and extensive payload protection systems. Of course, such a suborbital rocket cannot reach orbit on its own. It needs Starship to "push" it with externally pulsed propulsion.

Figure 3: A fun and of course very technically accurate cartoon about a suborbital rocket's ΔV limitations

Starship launches PuffSats for externally pulsed propulsion into a highly eccentric orbit around Earth, with a low $200\,\mathrm{km}$ perigee and a high apogee. These PuffSats move near Earth's escape velocity at perigee. The suborbital rocket intercepts the PuffSats with its pusher plate and rides their momentum pulses to low Earth orbit. While this approach reduces payload capacity compared to a single rocket system, most satellites are unable to take advantage of Starship's enormous payload volume anyway.

3.2 The 200 Mile High Club

SpaceX proposes direct Earth-to-Earth travel [24], ballistically launching passengers directly between cities with Starship from offshore platforms. This idea faces significant challenges:

- **Marine Environmental Impact:** Noise pollution from sea launches could severely harm marine ecosystems, including dolphins and whales.
- **Noise Over Populated Areas:** Starship's descent would generate loud sonic booms over cities.
- **Logistical Inefficiency:** Offshore launch platforms, by necessity located far from land, would add hours to the journey for boarding and departure, undermining the benefit of rapid travel.

A suborbital rocket plane offers a more practical alternative. To reach orbit, the suborbital rocket requires propulsion PuffSats launched by the Starship. Starship can be launched from remote locations where noise pollution is acceptable. Our suborbital rocket plane could take off from conventional urban airports using standard aircraft engines, then switch to rocket propulsion at high altitudes over remote areas to "skip" above the atmosphere and intercept Starship's propulsion PuffSats. While normal airports can handle kerosene or methane fuel, most lack the infrastructure for cryogenic liquid oxygen.

However, two solutions address the liquid oxygen challenge:

- **Air-breathing Scramjets (Optimistic Scenario):** If economical passenger scramjets become feasible, rockets could accelerate to around Mach 7 before a steep climb, eliminating the need for liquid oxygen. This would also reduce propellant mass. Unfortunately, the extreme stress on the airframe makes suborbital rockets more economically viable for the foreseeable future.
- **Mid-air Oxygen Refueling:** Suborbital rocket planes could receive liquid oxygen from specialized aircraft launched from airports equipped with liquid oxygen storage. This avoids retrofitting every urban airport, requiring only a single, strategically located airport near major destinations. Mid-air refueling also reduces our rocket plane's takeoff weight.

A formation of propulsion PuffSats launched in an eccentric Keplerian orbit could only propel the rocket plane on trajectories that bisect the Earth. Since most urban destinations would not align with such trajectories, the rocket plane needs to fire an adjustment burn at least once to reach the destination. Alternatively, a second set of propulsion PuffSats could intercept the rocket plane mid-flight and adjust its trajectory. Furthermore, to avoid a sonic boom upon descent, the plane must decelerate before atmospheric reentry. This deceleration could be provided by yet another set of propulsion PuffSats that were traveling in a retrograde orbit relative to the plane. These reentry PuffSats could be in a circular low Earth orbit rather than a high eccentricity orbit, significantly reducing the mass required.

4 I Love ISRU. Cheaper Externally Pulsed Propulsion *Without* Giant Reusable Rockets

For externally pulsed propulsion of intercity passengers to achieve genuine economic competitiveness, the cost of launching propulsion PuffSats must be exceptionally low. The rocket plane must be robust enough to guarantee on-time takeoffs and avoid missing its initial PuffSat rendezvous. Rocket acceleration and passenger cabin vibrations must be limited for infants and other susceptible passengers, further increasing costs and ΔV. Even highly reusable rockets may prove too expensive, limiting this technology primarily to the very high-end private luxury aviation market. While luxury aviation customers typically prioritize flexibility, PuffSat propelled flights necessitate advance scheduling. Despite these limitations, the potential market for affluent travel between cities like Dubai and Dallas is likely at least an order of magnitude larger than the satellite market.

Still, it would be disappointing if we can't make suborbital travel mainstream. If we can launch our PuffSats without giant rockets, we can reduce cost. After all, "the best part is no part," [50] and a reusable rocket is one heck of a part.

4.1 Lunar Volatiles For Externally Pulsed Propulsion

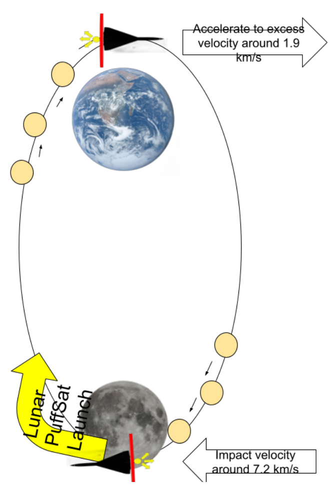


Figure 4: Lunar launched PuffSats replace Starship launched PuffSats [57] [25]

Instead of using Starship, lunar volatiles extracted from the moon's permanently shadowed regions could fill our propulsive PuffSats. As shown in Figure 4, these PuffSats could be sent into a trans-lunar injection orbit that intersects our terrestrial suborbital rocket plane. Although PuffSat skins and electronics would likely still be sourced from Earth, volatiles constitute the majority of the PuffSats' mass. One approach to launching these PuffSats into orbit involves using rockets powered by lunar-derived propellants. The space community is enthusiastic about water electrolysis to produce and store cryogenic fuel for lunar rockets [1]. However, this process is energy-intensive and requires complex cryogenic infrastructure, particularly for hydrogen fuel. Moreover, a reusable lunar rocket designed for repeated landings would require approximately $6\ \mathrm{km/s}$ of ΔV, necessitating propellant mass fractions of about 75% for hydrogen or 81% for methane. While these figures are an improvement over Earth-launched rockets, the high propellant mass fractions remain a significant challenge.

4.2 Lunar Rockets Without Lunar Rocket Fuel

Instead of launching our lunar volatiles towards Earth with conventional rocket fuel, we launch off the moon using the same externally pulsed propulsion we've been discussing for terrestrial launches. A rocket launched with externally pulsed propulsion from the lunar surface into a trans lunar injection orbit can burn its engines at periapsis around Earth. Due to the Oberth effect, a small burn near Earth returns the rocket to the moon with a large velocity change. As the rocket approaches the moon, it deploys its payload of PuffSats previously filled with lunar volatiles. These returning PuffSats can push a new, more massive rocket filled with fresh volatiles off the moon. We can then repeat this cycle for exponential growth in lunar PuffSat launch mass capacity. We've reduced combustible fuel requirements by burning our rockets near Earth.

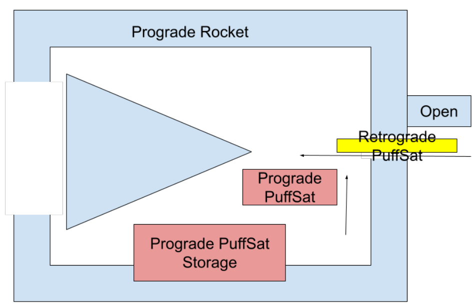
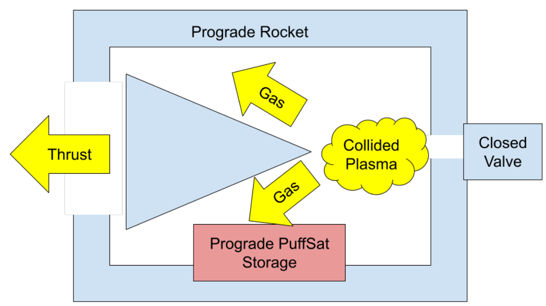
Before Collision	After Collision
	

Table 3: A pulsed propulsion chamber. PuffSats enter, collide and produce thrust. The valve, likely a fast rotating door synchronized with PuffSat arrivals, is optional because a small front opening will produce less thrust than a large rear opening. If the explosion turns the gas into plasma, the valve could be magnetic rather than solid state.

However, we ideally don't want to make any chemical rocket fuel at all. Let's again use external propulsion to launch our PuffSat deployment rocket from the lunar surface into a trans-lunar orbit. We also launch a second set of PuffSats from the lunar surface into a retrograde trans-lunar orbit. Using the millimeter precision navigation techniques we've discussed, we sequentially collide these retrograde PuffSats with more massive prograde PuffSats the main rocket is carrying. As depicted in Table 3, we trap the exploding gas from these collisions in a pulsed propulsion chamber and redirect this gas for thrust. To leverage the Oberth effect and maximize gas collision velocity, we collide our PuffSats close to periapsis near Earth.

If our colliding PuffSats each travel at $v = 11\,\mathrm{km/s}$, then from Equation 12 derived in Appendix B, the maximum theoretical combined effective exhaust velocity is $v_e = \frac{1}{2}v = 5.5\,\mathrm{km/s}$. Suppose this pulsed explosion has significant real world losses for an effective exhaust of $v_e = 3\,\mathrm{km/s}$. If the main rocket accelerates at its Earth periapsis with a burn of $1.9\,\mathrm{km/s}$ it will reach the moon at $7.2\,\mathrm{km/s}$ [20]. If the rocket deploys propulsion PuffSats on lunar approach, they can push another rocket off the moon with a mass greater than the incoming PuffSats. Specifically, the incoming propulsion PuffSats have enough momentum to start an exponential growth cycle where each loop around the moon launches about 1.455 times the starting mass. If we do this once per lunar month, we have increased our initial launch mass capacity by a factor of 1 million in about 2.8 years [20].

4.3 Lunar Oxygen Has Mass And All It Needs

Lunar volatiles like water ice are ideal for filling PuffSats, but they are scarce. However, oxygen is very common in lunar surface minerals. Using solar energy and mining rovers derived from platforms like the IPex Pilot Excavator [31], we can produce oxygen. On the volatiles depleted sunlit lunar surface, finding something to burn oxygen with for rocket propulsion is hard. However, externally pulsed propulsion does not require oxygen combustion, just gas momentum. In shadowed craters or artificial shade, lunar derived oxygen will liquify and perhaps even solidify for storage.

We use some of our lunar PuffSats for the externally pulsed propulsion to lift terrestrial suborbital supply rockets into low Earth orbit. The supplies include solar panels, pusher plates, PuffSat skins, electronics, and rovers. These supply rockets then use conventional engines to gain ΔV so they can resupply our lunar surface operations. When they reach the moon, we also use externally pulsed propulsion to decelerate for lunar landing. The deceleration propulsion PuffSats would previously have been launched from the moon's surface into an eccentric lunar orbit opposite to the incoming supplies' velocity. We can optionally reduce terrestrial resupply requirements by embracing basic lunar manufacturing using metals like iron that are byproducts of lunar oxygen production. These lunar metals could be shaped into pusher plate and pulsed propulsion chamber components.

We use the rest of our lunar PuffSats to exponentially grow our PuffSat mass capacity in orbit using the Oberth cycle discussed in subsection 4.2. Oxygen production is very energy intensive and lunar regolith will likely degrade machinery somewhat faster than equipment would degrade on Earth. Nevertheless, regolith resistant machines may still enable propulsion at costs that make hypersonic travel scalable.

4.4 Lunar Paleontology: Ancient DNA From Lunar Volatiles

In subsection 4.2, we explored using lunar volatiles from permanently shadowed craters for externally pulsed propulsion. These extremely cold craters could also indefinitely preserve DNA and other biomolecules from Earth impact ejecta [10]. We could check the volatiles we're extracting to see if they contain homochiral organic molecules, which are only produced by living organisms. Studying samples that contain homochiral molecules would offer a unique window into Earth's entire biological history, potentially revealing how life began. And, of course, the discovery of dinosaur DNA would surely delight *Jurassic Park* [8] fans.

5 Sorry, I Don't Need ISRU

5.1 The Need For Speed [36]

If our propulsion PuffSats can reach high enough velocities, we could directly launch terrestrial payloads heavier than the PuffSats themselves. This would eliminate the need for lunar ISRU. Repeatedly executing this launch cycle with ever larger (or more numerous) payloads would enable exponential growth in our launch capacity. Consider a rocket launched from Earth carrying pulsed propulsion payload. We send $\frac{3}{4}$ our payload on a prograde trajectory with a solar periapsis similar to the Parker Space Probe and the remaining quarter on the opposing retrograde trajectory with the same Sun grazing periapsis. These trajectories require high ΔV but we can use Jupiter gravity assists to achieve them (See subsection 5.5). These payloads release micro-thrust precision steered projectiles (see subsection 5.3) which then collide sequentially at periapsis in a pulsed propulsion chamber as described in Appendix B. The resulting plasma can produce effective exhaust velocities of $100\,\mathrm{km/s}$ or higher. Perhaps we accelerate from $200\,\mathrm{km/s}$ to $250\,\mathrm{km/s}$ with Earth crossing speeds around $150\,\mathrm{km/s}$ [20]. At these Earth crossing velocities, incoming PuffSats could collide with PuffSats aboard a new terrestrial rocket in the rocket's propulsion chamber. With the thrust from these collisions, our payload would then be sent on prograde and retrograde orbits with low solar periapsis, repeating the cycle. If desired, we can optimize exhaust velocity further by lowering the periapsis in steps, allowing our payload to fall significantly towards the Sun after each step. This way, collisions after each periapsis reduction occur at progressively higher velocities for greater effective exhaust velocity. If we double payload mass every 6 months, we increase our initial payload by a factor of 1 million in less than a decade [20].

5.2 Radiative Differences From Project Orion

Project Orion required shaped explosives to redirect plasma towards the pusher plate because 80% of the bombs' energy became black body X-ray thermal radiation [46]. In contrast, our proposed system anticipates minimal radiative losses from collisions, even at speeds matching the Parker Solar Probe. Though detailed computer analysis is needed for full confirmation, our reasoning for this low loss stems from

- The colliding atoms in our system have a much lower atomic mass than fissile atoms. For a given total kinetic energy, this means the energy is distributed among a greater number of particles, resulting in a significantly lower average kinetic energy per particle, which directly translates to lower plasma temperatures. Additionally, plasmas formed from lighter elements generally have a higher specific heat capacity, meaning they absorb more energy for a given temperature increase.
- The mean velocity of colliding atoms is likely about $\frac{1}{5}$ that of atoms in an inefficient 1% yield bomb. Since kinetic energy is proportional to the square of velocity, this alone suggests peak temperatures at least 25 times lower.
- Combined, lower mean velocity and atomic mass imply temperatures might be 200 times less in our collision than in a bomb. Radiative power rises with the fourth power of temperature (T^4), so peak radiation flux is likely around 1 billion times less than the least efficient nuclear bombs.
- The colliding masses should be much smaller than a nuclear bomb, with a lower radiative surface area. As the collision plasma expands adiabatically, its volume increases proportionally faster relative to its initial volume

compared to a larger bomb plasma for a given absolute linear expansion. This more rapid proportional change in volume leads to a quicker and more substantial decrease in temperature, further reducing radiative output.

Lower temperatures generate longer-wavelength blackbody X-rays compared to those from bombs. This means materials with lower atomic numbers (lower Z) can absorb this radiation and keep the plasma opaque. While Project Orion favored expensive and difficult to work with tungsten [46], these longer wavelengths should allow for the use of cheaper elements to achieve opaque plasma.

5.3 Solid Projectiles Rather Than Low Density PuffSats

Given the extreme velocities at periapsis, we no longer collide low density PuffSats because solid objects vaporize into opaque plasma. The real-world efficiency of these plasma explosions is likely high because the extreme temperatures should bring the entire plasma to thermal equilibrium before significant expansion occurs.

We'd make these solid projectiles primarily from cheap low atomic number (low Z) materials like boron nitride, motor oil, and graphite. A small amount of cheap higher Z materials like iron would be included to ensure opacity to the blackbody X-rays produced. All the projectile's mass contributes to propulsion, irrespective of its composition. The projectiles can contain electronics, heat shielding, and some liquid that passively or actively cools the skin through convection. They can also partially be made from batteries so that solar power is not needed too close to the Sun.

5.4 Navigation Challenges Near Periapsis

Close solar periapsis involves some unique challenges. Obviously, any sensor dependent on visible light will need to filter interfering solar illumination. Instruments will need to handle heat and solar wind. Relativistic influences perturb the craft more than they would on Earth. High collision speeds demand extremely accurate navigation. The pulsed propulsion chamber may ablate slightly on each pulse. The impacting projectiles must be miniaturized to at most a few kilograms to contain the immense energy from explosions at these velocities.

Perhaps the most significant nuance is the need to adjust for solar weather. Since this weather influences luminosity, it also influences radiation pressure. Fortunately, neural networks appear capable of improving weather predictions [26].

Spacing PuffSats sequentially far apart may be hard. Objects far apart at periapsis get closer together as radial distance grows. As a result, Earth distance propulsion PuffSats would need to impart relatively high acceleration in short times. However, the terrestrial payloads we're directly accelerating this way should be unmanned.

When we lift high value payloads like astronauts into Low Earth Orbit, we use two sets of propulsive PuffSats. First, our Earth crossing PuffSats from the Sun push unmanned payloads into eccentric orbits around Earth. Then these eccentric payloads deploy PuffSats to push vital cargo like people or satellites just as we discussed in subsection 3.2.

5.5 Initial Periapsis Orbits With Jupiter Gravity Assists

A final issue is placing the initial payload in a retrograde low periapsis solar orbit. The best approach for this is likely using a gravity assist from Jupiter, which was the original plan for the Parker Space Probe mission [33].

To operate far from the Sun without large solar arrays, the spacecraft could rely on fuel cells or batteries. If the fuel cells or batteries have volatile reaction products like water vapor, these products can be harvested for PuffSats gas production. Near Jupiter, the PuffSats volatiles would freeze and serve as effective radiation shielding. Together, the internal power source and shielding infrastructure would permit a close Jupiter flyby that maximizes our gravitational slingshot.

Optionally we can push more mass into the initial orbit by using a Jupiter gravity assist (possibly with a burn at Jupiter to leverage its Oberth effect) to place propulsion PuffSats into a retrograde Hohmann trajectory back to Earth. They would cross Earth at around $69\,\mathrm{km/s}$, which could push a larger terrestrial payload onto prograde and retrograde colliding trajectories at low solar periapsis.

5.6 Jupiter Only Exponential Launch Growth

A simpler way to bootstrap an exponential launch cycle is to use the retrograde Hohmann trajectory from Jupiter described in subsection 5.5 but without close solar approaches. PuffSats returning from Jupiter can push more than 9 times their weight into a highly eccentric orbit around Earth. A small conventional burn coupled with solar electric engines and gravity assists with the inner planets can return this payload to Jupiter and restart the cycle. The growth is slow compared to other proposals but may provide sufficient launch capacity to supply the satellite market within 2 decades.

We can also combine this Jupiter launch cycle with reusable rockets or the lunar ice based cycle discussed in subsection 4.2. By increasing the number of initial PuffSat launches toward Jupiter, we can more rapidly scale up our launch throughput. Once this throughput is established, Earth based payloads can ride the returning PuffSats to orbit, enabling a sustainable and repeatable launch cycle.

6 One Hiroshima Per Second. The World Set Free

In subsection 5.1, we propelled PuffSats to $150\,\mathrm{km/s}$ at $1\,\mathrm{au}$ using solar gravity and externally pulsed propulsion. A $60\,\mathrm{TW}$ pulsed heat source, which is equivalent to one Hiroshima bomb per second [60], requires harnessing the kinetic energy of just $5.3\,\mathrm{t/s}$ of propulsion mass at these speeds. For context, humanity's total power consumption is approximately $20\,\mathrm{TW}$ [44]. Given that typical power plants are roughly one-third efficient, a single one of these pulsed heat sources could meet the energy needs of all human civilization. Remarkably, this concept evokes H.G. Wells's prophetic vision in his 1913 novel, *The World Set Free*, where he imagined atomic bombs as a "blazing continual explosion" [56].

Using kinetic projectiles to generate terrestrial power only makes sense if it achieves massive economies of scale that outperform the linear costs and land use efficiency of conventional renewables. Let's explore how to build such a truly ambitious megastructure, and then explain why it's economically attractive in subsection 6.4.

6.1 Straw Ways To Heaven

The most common proposal for utilizing space-based power on Earth involves wireless power transfer from orbiting power plants to terrestrial rectenna arrays [29]. Unfortunately, long distance wireless transfer requires breakthroughs in wireless beam focusing [64] and large radiators for dissipating heat. Moreover, the required wireless transmission infrastructure, both in space and on Earth, would be colossal. Given these challenges, let's investigate terrestrial solutions which directly convert kinetic impact energy to electricity on Earth.

To deliver kinetic energy projectiles to Earth, the projectiles must be able to withstand atmospheric entry. One solution is to build a vacuum tunnel, extending from Earth's surface to space, precisely aligned to allow incoming projectiles to pass through unimpeded. The tunnel is suspended from an anchor point as depicted in Figure 5. Enthusiasts have proposed numerous physically plausible structures that could support an anchor hoisted above Earth's atmosphere. These include Lofstrom Launch Loops [22], tethered and global orbital rings, space elevators, and space fountains [2]. However, these ambitious ideas generally suffer from very low Technology Readiness Levels (TRLs), meaning they are far from practical implementation.

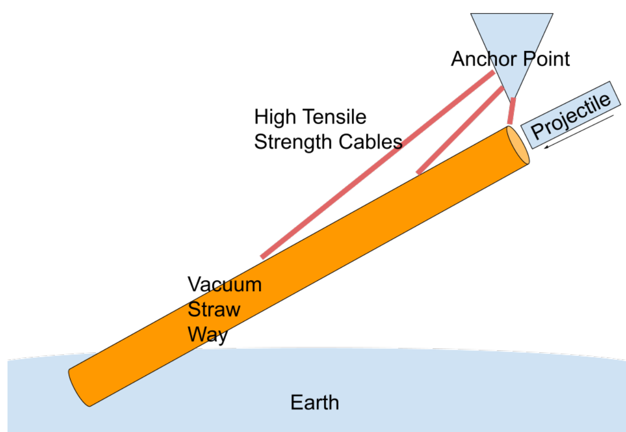


Figure 5: Vacuum tube suspended from cables allows projectiles through the atmosphere

Fortunately, externally pulsed propulsion offers a promising path to position an anchor point above Earth. While this technology also lacks significant technical maturity, we would have already developed it to highly reliable standards if we were using it to direct projectiles at Earth using the techniques from subsection 5.1.

A heavy lift rocket, such as SpaceX's Super Heavy [65], lifts the anchor point (and the vacuum tube it is connected to) to its initial height. We then indefinitely hover the anchor point using equal mass PuffSats that collide head on in a pulsed propulsion chamber (described in subsection 4.2), redirecting thrust downward. The propulsion chamber exhaust can be angled slightly to provide thrust vectoring to counter atmospheric winds on the vacuum tube and support cables. A reaction control system on the anchor point adjusts the pulsed propulsion chamber so it stays precisely positioned for the next PuffSat collision. If these PuffSats meet at $v = 11\,\mathrm{km/s}$ at an average mass flow rate of $1\,\mathrm{t/s}$ they can theoretically suspend more than $1100\,\mathrm{t}$.

In reality, energy losses would reduce thrust. For robust operations, we would need to lift redundant anchor points and vacuum tubes. Together, redundancy and energy losses imply we will need additional external propulsion collision mass per second. Nevertheless, lifting a few tons per second of propulsion PuffSat mass from Earth (as in subsection 3.2) or the moon (as in subsection 4.2) seems economically viable if we use our vacuum tube to cleanly produce all the energy required by mankind.

6.2 Vacuum Tube Details

Our proposed vacuum tube should have tapered walls since preserving a vacuum at higher elevations only requires simple thin barriers. The tube's optimal form will be maintained by cables with adjustable lengths connected to a central anchor point. The tube can curve to compensate for Coriolis forces during projectile flight. The anchor point itself will rotate throughout the day to track the Sun.

To keep the vacuum tube aloft, external propulsion will be employed, even during inactive nighttime hours. Alternatively, for maintenance, the tube could be lowered at night and then re-hoisted by a heavy-lift rocket the following day.

Creating a high vacuum in long tunnels presents a challenge, though it's successfully achieved in facilities like the Large Hadron Collider. Fortunately, our system benefits from the projectiles themselves acting as a natural vacuum pump. Stray atoms will tend to be bounced downwards by projectile collisions. While some atoms may sputter off the projectiles, these will also be directed downwards. Ultra high vacuum equipment at the bottom of the tunnel will effectively remove these atoms, ensuring the vacuum remains strong.

Projectiles that catastrophically miss the vacuum tube cause only moderate Chelyabinsk level [42] ground effects because their extreme velocity guarantees they burn up at high altitudes. Assuming our vacuum tubes are in remote areas, this causes minimal disturbances to population centers. The vacuum tube itself is likely destroyed, but redundant vacuum tubes would then be moved into place.

6.3 Power Plant And Vacuum Air Lock Exchange Details

Beneath the vacuum tube, we propose excavating a massive steam chamber designed to vaporize incoming projectiles. These chambers would be substantial construction projects, engineered to withstand sudden changes in pressure and temperature. Suppose a $0.1\,\mathrm{km}^3$ steam chamber containing $50\,\mathrm{kg/m}^3$ steam receives a $600\,\mathrm{TJ}$ kinetic impact. As a simplification, let's say the steam has a constant specific heat of $3.5\,\mathrm{kJ/(kg°C)}$. In this case the temperature change is $\frac{600\,\mathrm{TJ}}{5\times10^9\,\mathrm{kg}\times3500\,\mathrm{J/(kgK)}} = 34.2\,°\mathrm{C}$. An impact of this magnitude every 10 seconds produces the heat to continuously provide all humanity's energy. This steam chamber would be connected to thousands of turbines and a massive cooling loop to harness and dissipate this energy.

Releasing large amounts of heat into the atmosphere would lead to unacceptable local temperature increases. Using a coolant loop that exchanges heat with deep ocean water will also have environmental consequences. Spreading $40\,\mathrm{TW}$ of heat over $10\,\mathrm{km}^3$ of deep ocean water would increase its temperature by $\frac{40\,\mathrm{TW}\cdot 3600\,\mathrm{s/h}}{1\times10^{13}\,\mathrm{kg}\cdot 4186\,\mathrm{J/(kg\,°C)}} = 3.44\,°\mathrm{C/h}$. This rapid temperature change could severely damage local marine habitats.

However, considering the limited marine life found far above the ocean floor and below the sunlit zone, the broader deep sea ecology beyond the directly heated zone would remain stable. When compared to the widespread impacts of global anthropogenic climate change or even the significant displacement of wildlife from building solar farms, the environmental harm from this specific heat rejection method appears minimal.

An air lock separates the steam chamber from the rest of the tunnel as shown in Figure 6. A spinning door with a tip speed of $300\,\mathrm{m/s}$ could close a $30\,\mathrm{cm}$ diameter aperture in $1\,\mathrm{ms}$. Even a $5\,\mathrm{m}$ long air lock is long enough to prevent steam molecules from traversing the air lock in this short time. We swap in a new air lock segment between kinetic projectile impacts. This gives us time to restore the high vacuum in the airlock segment before it's used again.

6.4 With Economies Of Scale, Our Ambitions Can Scale Too

While a global power plant requires a massive initial capital investment, its costs scale favorably with output. The cost of suspending a large vacuum tube depends very little on the plant's generating capacity. The cost of deep sea cooling loops would also be amortized across the entire planetary scale facility. A multi-terawatt installation could achieve significant per-watt cost reductions through bulk procurement of thousands of identical turbine and generator units.

Mass production reduces the cost of projectile electronics and micro thrusters. The cost of these components per projectile also remains nearly the same as individual projectile size increases. Ten seconds of planetary scale power corresponds to $20\,\mathrm{TW} \times 10\,\mathrm{s} \approx 5.56 \times 10^7\,\mathrm{kW\,h} = \$555,556$ at 1 cent per kilowatt-hour. This energy cost would likely dwarf the material costs of the projectiles themselves.

Power from our plant could be globally distributed by super tanker sized batteries that connect to urban power grids at coastal ports. While the cost of utility-scale batteries is progressively declining, it remains a significant hurdle. Current battery designs prioritize efficient energy storage and release. However, if energy efficiency becomes less critical, we

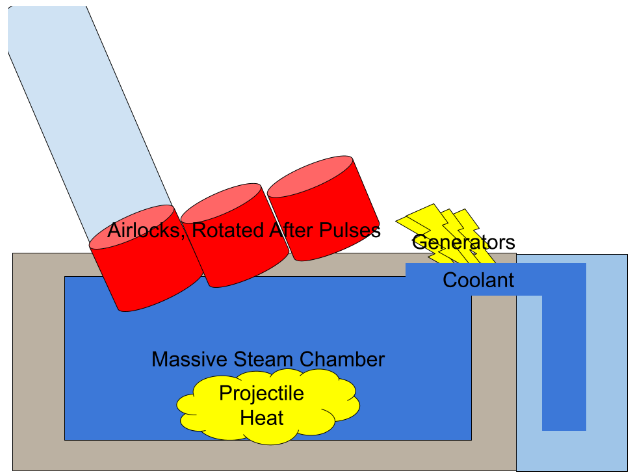


Figure 6: The power plant and vacuum air lock exchange. Air lock segments are rotated to give time to restore high vacuum between uses.

could design cheaper low performance batteries. Given that our power source exhibits strong cost efficiencies, we could simply increase the power output to compensate for any energy losses incurred by using these more affordable batteries for distribution.

Batteries are environmentally attractive, but our world still depends heavily on fossil fuels. Very low cost power can cheaply produce hydrocarbon fuels from water and carbon dioxide. The hydrogen can come from electrolysis, while carbon dioxide comes from biomass, heating carbonates, industrial waste, or direct air/ocean capture.

Though the power plant and distribution infrastructure would cost billions to construct and operate, the revenue generated is staggering. Ultimately, we'd spend billions to make trillions annually from a planetary-scale plant. Turns out, if *Superman* wants to be as rich as *Lex Luthor*, he should get limitless energy not from the light of a yellow sun, but from its gravity [51].

6.5 Comparison To Project PACER

Project PACER was a 1970s Los Alamos concept to generate power by extracting steam from nuclear bombs detonated in a salt cavern [35]. Later improvements protected the cavern walls with an artificial waterfall of tritium breeding liquid salts [4].

Unlike PACER, our proposal does not produce radioactive waste or encourage the mass production of nuclear weapons. Should a liquid wall be needed to protect the chamber, it can be made from cheap materials like water. Tritium breeding and extraction are not required. Most critically, our design eliminates the need for a biological shield, simplifying the direct coupling of steam to turbines. This direct steam cycle enables the rapid heat exchange with the environment necessary to build terawatt-scale power plants.

6.6 To Solve Climate Change, Make The Earth A Death Star

A Death Star [58] is a giant sphere with a narrow 1 meter opening where you can shoot something down to create an explosion inside the main reactor. Building a Death Star from scratch would be a huge undertaking. Fortunately, if we build the Straw Way To Heaven described in subsection 6.1, we're living on one. Although our Straw Way generator produces clean energy from incoming projectiles, its power production is restricted to daytime hours when the straw can face the sun. Also, a limitless clean energy source would only slow climate change. Industrial carbon emissions from steel, cement, agriculture, and other processes would still heat the planet [6].

6.6.1 That's No Moon [23]. Oh Wait, It's Literally Our Moon

Projectiles made from lunar materials could enter a terrestrial Straw Way from high angles of attack around the clock. Lunar regolith is primarily carbon depleted rock [34]. If this rock was heated, vaporized, and pressurized as it fell into deep ocean water, it would rapidly absorb carbon dioxide to form carbonates that negate industrial carbon pollution.

To generate $60\,\mathrm{TW}$ of heat from lunar bombardment, we'd need an astonishing $1\,\mathrm{kt/s}$ of lunar mass to pass through the terrestrial vacuum tube. Such a vast quantity is daunting, but the momentum for launching off the moon could come from kinetic projectiles inbound from the Sun (as described in subsection 5.1). Beyond providing thrust, these projectiles aimed at the Moon could vaporize lunar regolith. The resulting thermal energy could be harnessed for electricity generation or to power chemical and industrial processes directly. This lunar power source could support large scale mining and production of the oxygen gas used in externally pulsed propulsion (as discussed in subsection 4.3).

6.7 Fusion Propulsion And Epstein Drives

The fast projectiles from subsection 5.1 could propel a spacecraft around the inner solar system at relatively high speeds. As our technology advances, we'd want to travel on brachistochrone trajectories under constant Earth gravity acceleration between the planets as envisioned in *The Expanse* [7]. Evaporative cooling and advanced heat shields like NASA's yttrium oxide based "solar white" might enable spacecraft to approach the Sun to 2 solar radii [52]. At this close solar periapsis, prograde and retrograde projectile collision velocities would exceed $869\,\mathrm{km/s}$ [20] in the reference frame of a fusion pulsed propulsion chamber on the target rocket.

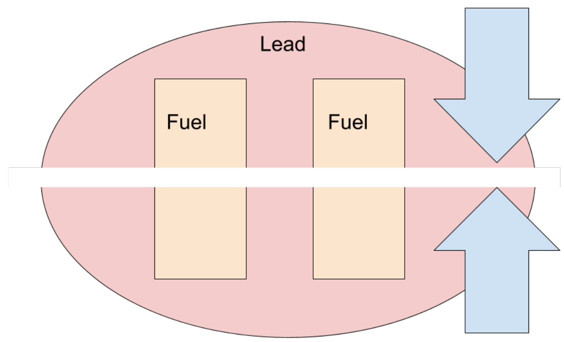


Figure 7: A lead tamper generates immense shock heating around fusion fuel and compresses it to ignition conditions during head-on collisions.

A 1979 Los Alamos Impact Fusion workshop concluded speeds of just $200\,\mathrm{km/s}$ might be sufficient for precompressed gram sized fusion fuel projectiles to ignite [41]. Larger projectiles would likely be easier to confine long enough for high fusion energy gain. A lead tamper, as depicted in Figure 7 surrounding a few hundred grams of fusion fuel could ignite fusion explosions and trigger immense exhaust velocities. Pulsed fusion propulsion would likely employ the shaped nuclear charges Project Orion explored to redirect energy and thrust. With mostly aneutronic fusion fuel, projectiles could achieve velocities up to $20\,000\,\mathrm{km/s}$. This is because aneutronic fusion directly converts energy into charged particle kinetic energy, bypassing the mass penalty of neutron shielding. A seed of deuterium-tritium could ignite a larger deuterium and helium-3 mixture to achieve aneutronic fusion rocket speeds. As the spacecraft accelerates, it can also reach speeds where it triggers fusion by crashing into slower moving fusion fuel targets. If carefully planned, these chains of fast-moving projectiles could essentially create interplanetary highways, allowing people to travel between planets under comfortable Earth gravity in time frames comparable to ocean liners crossing the Atlantic.

6.8 The Sixth Question For Climate Change

Bill Gates' excellent book, *How to Avoid a Climate Disaster* [14], details five practical questions [11] any effective climate solution must address. Our Straw Way to Heaven (see subsection 6.1) addresses Gates' questions better than other alternatives. It completely negates carbon emissions, reverses cement emissions, provides indefinite global power, occupies minimal space, and boasts marginal costs that decline rapidly with output.

Yet, I respectfully propose a sixth crucial question for public acceptance of any global warming solution: Beyond just reducing our electric bills, how will this breakthrough drastically improve daily life? An investment on the scale required to solve climate change should ideally grant human society new abilities, such as hypervelocity transport and affordable space travel. Externally pulsed propulsion can achieve all of these things.

7 When We Get Greedy, We'll Go To Phoebe

In subsection 5.1 we discussed using Sun grazing Oberth maneuvers to accelerate projectiles to $150\,\mathrm{km/s}$ at $1\,\mathrm{au}$. These high velocities give the projectiles enough energy for the high ΔV required to place the next suborbital rocket into prograde and retrograde colliding orbits near the Sun. Such close approaches introduce significant challenges, as detailed in subsection 5.4. These difficulties could increase projectile costs compared to those making less extreme solar approaches.

Orbits with higher apoapsis require less ΔV to shed orbital angular momentum and significantly lower their periapsis. For example, transferring to a solar impact trajectory from Saturn requires only about $10\,\mathrm{km/s}$, compared to roughly $30\,\mathrm{km/s}$ from Earth. This makes Saturn a more efficient departure point for reaching the inner solar system or the Sun.

Saturn's irregular moon Phoebe lies just $180° - 173.4° = 6.6°$ off the solar ecliptic [66], making it well aligned for interplanetary transfers. It orbits at high elevation with a relatively slow velocity relative to Saturn, offering low ΔV transfers to orbits reaching close to Saturn. A prograde rocket launched from Phoebe could collide with retrograde payloads also launched from Phoebe. These collisions could occur in a pulsed propulsion chamber near Saturn, enabling high efficiency Oberth maneuvers. With precise planning to avoid Saturn's rings, this method could launch spacecraft toward the inner solar system.

These rockets can also return to Phoebe at high speeds to launch more mass towards Saturn with pulsed propulsion, enabling a bootstrapped launch mass growth cycle similar to the terrestrial moon cycle discussed in subsection 4.2. Power for mining Phoebe can come from solar energy concentrated from lenses built with Phoebe's native ice or from plastic made on Phoebe. Alternatively, thermal energy generated by returning impactors could power mining on Phoebe.

If Phoebe's low gravity poses excessive challenges for keeping mining infrastructure grounded, Iapetus is a backup alternative. Similarly, Jupiter's moon Himalia may support analogous maneuvers if exploration discovers it has significant volatiles.

7.1 Mining Helium-3

Helium-3 for aneutronic fusion may be available on the Earth's moon [12], but likely not in quantities to support large scale fast interplanetary transport like discussed in subsection 6.7. However, the gas giants contain inexhaustible supplies of helium-3 [40]. A nuclear fission thermal rocket or scram jet could extract helium 3 and hydrogen while flying in Saturn's atmosphere and then jump a few thousand kilometers above the atmosphere. It could then separate from a payload carrying mined Helium-3, falling back to Saturn to mine more. An accident on such a fission rocket would cause no harm, because waste would simply fall into Saturn's core. Propulsion PuffSats from Phoebe could then send the Helium-3 payload into the inner solar system for use in fusion rockets.

If fission rockets prove politically unpalatable, chemical rockets may also work. Chemical rocket fuel powers a motor in Saturn's atmosphere for the energy to mine helium-3. The rocket then fires its rockets to hop above Saturn's atmosphere. Propulsion PuffSats from Phoebe push the rocket into a stable orbit where it is refueled and releases its helium-3 payload. Then new propulsion rockets decelerate the refueled rocket so that it falls into Saturn's atmosphere for another mining round.

8 War, Policy, And Pulsed Propulsion

8.1 Fusion Rockets And The Outer Space Treaty

The Outer Space Treaty [53] prohibits nuclear weapons in space. The legality of pure fusion rockets like those discussed in subsection 6.7 requires clarification, likely through international dialogue and new legal frameworks.

8.2 Hackers Must Be Prevented From Causing Catastrophic Explosions

As previously discussed, the energy projectiles for the *Death Star* discussed in subsection 6.6 are intentionally designed to burn up high in the atmosphere without causing damage in case of a mishap. However, there is a danger a hacker could manipulate microthrusters on the projectiles to enter the atmosphere simultaneously rather than in sequence, leading to larger Tunguska [28] sized multi megaton explosions. We can mitigate this risk with standard software security practices like using memory safe languages and authenticated communication.

8.3 Risk Of PuffSat Sabotage

Externally pulsed propulsion might be useful for launching military assets like Golden Dome [32] or the Brilliant Boulders [21] discussed on the blog related to this paper [45]. The PuffSats described in subsection 4.2 are likely vulnerable to destruction from high powered terrestrial lasers by a military adversary. Nations will need to defend their payloads from sabotage by hostile actors.

8.4 Aviation Clearance Needed For Straw Ways

Since the Straw Way To Heaven (see subsection 6.1) is a fixed structure in the sky, we will need regulations to ban aviation next to it. This seems feasible given the straw way will be placed in a remote area. The host nation must also guard the Straw Way against sabotage.

9 Conclusion And Future Directions

This paper has introduced the transformative potential of externally pulsed propulsion. We've demonstrated how its intricate navigation, made viable by advancements in neural networks and CubeSat formation flying, could revolutionize hypersonic intercity transport. It also offers a novel approach to reverse global warming, provide limitless affordable power, and even enable human colonization of the solar system with fusion power.

Our next steps involve simulating the fundamental physics and prototyping the control software for externally pulsed propulsion, ensuring the most accurate simulations possible. We also plan to solicit feedback on current challenges impeding these concepts and assess their economic and technical surmountability.

If the basic physics of externally pulsed propulsion work, we'd likely proceed with different technologies in different time frames. A guess on when each technology should be fully developed is proposed in Table 4.

Time Frame	**Action**
Now	Prototype satellite launch and hypersonic travel using externally pulsed propulsion from PuffSats launched by large reusable rockets
Now	Prototype satellite launch using reverse Hohmann transfer from Jupiter as described in subsection 5.6
Near Term	Prototype launches using lunar volatiles or mined lunar oxygen instead of large reusable rockets
Mid Term	Prototype leveraging close solar approaches or material from Phoebe/Saturn for externally pulsed propulsion
Mid to Long Term	Prototype constructing a Straw Way to Heaven and energy infrastructure based on it
After the Singularity (Far Distant Future)	Prototype fusion rockets and interplanetary highways

Table 4: Proposed schedule for future work

Marc Andreesen once said "software is eating the world" [30]. If control software enables externally pulsed propulsion, it will devour the solar system as well.

A Derivation Of PuffSat Mass/Rocket Mass Continuous Approximation

We want to approximate the ratio of the total PuffSat mass m_p with all PuffSats traveling at velocity v_p for a sequence of PuffSats to push a rocket with mass m_r with initial velocity v_{ri} to final velocity v_{rf}. Let's initially naively assume every collision is perfectly elastic in one dimension. We'll use calculus to get a closed form expression by solving for a rocket continuously bombarded by infinitesimal PuffSats each with mass dm_p. (Note: Grok [67] helped with some of the math for this derivation and parts of this derivation are copied from Grok results directly)

The initial velocities are

- Mass m_r: Velocity v_r.
- PuffSat: Mass dm_p, velocity v_p.

After the collision, let:

- Mass m_r: Velocity $v_r + dv_r$.
- PuffSat: Velocity v'_p.

A.1 By Conservation Of Momentum

$$m_r v_r + dm_p v_p = m_r(v_r + dv_r) + dm_p v'_p$$

$$m_r v_r + dm_p v_p = m_r v_r + m_r dv_r + dm_p v'_p$$

$$dm_p v_p = m_r dv_r + dm_p v'_p$$

$$m_r dv_r = dm_p(v_p - v'_p) \tag{1}$$

A.2 Velocity Change Of m_r

For an elastic collision

$$v'_p = \frac{2m_r}{m_r + m_p} v_r + \frac{m_p - m_r}{m_r + m_p} v_p \tag{2}$$

Since $m_r \gg m_p$ we plug $m_p = 0$ into Equation 2 and find

$$v'_p = 2v_r - v_p \tag{3}$$

Substituting v'_p from Equation 3 into Equation 1:

$$\begin{aligned} m_r dv_r &= dm_p(v_p - (2v_r - v_p)) \\ m_r dv_r &= dm_p(v_p - 2v_r + v_p) \\ m_r dv_r &= dm_p(2v_p - 2v_r) \\ m_r dv_r &= 2dm_p(v_p - v_r) \\ dv_r &= \frac{2(v_p - v_r)}{m_r} dm_p \end{aligned} \tag{4}$$

A.3 Integrate Over Many Collisions

The velocity of m_r changes from v_{ri} to v_{rf} as more PuffSats collide. Integrate Equation 4:

$$\int_{v_{ri}}^{v_{rf}} dv_r = \int_0^{m_p} \frac{2(v_p - v_r)}{m_r} dm_p$$

The left-hand side is:

$$\int_{v_{ri}}^{v_{rf}} dv_r = v_{rf} - v_{ri}$$

For the right-hand side, treat v_r as a function of the accumulated PuffSat mass m_p. However, we need to express v_r in terms of m_p. From Equation 4:

$$\frac{dv_r}{v_p - v_r} = \frac{2dm_p}{m_r} \tag{5}$$

Since v_p is constant, $dv_p = 0$ and $dv_r = -d(v_p - v_r)$, so we can rewrite Equation 5 as:

$$-\frac{d(v_p - v_r)}{v_p - v_r} = \frac{2dm_p}{m_r}$$

Integrate both sides: - Left: $\int_{v_p - v_{ri}}^{v_p - v_{rf}} -\frac{d(v_p - v_r)}{v_p - v_r} = \int_{v_{ri}}^{v_{rf}} \frac{dv_r}{v_p - v_r}$

$$= [-\ln|v_p - v_r|]_{v_{ri}}^{v_{rf}} = \ln\left|\frac{v_p - v_{ri}}{v_p - v_{rf}}\right|$$

- Right: $\int_0^{m_p} \frac{2dm_p}{m_r} = \frac{2m_p}{m_r}$ Equate:

$$\ln\left|\frac{v_p - v_{ri}}{v_p - v_{rf}}\right| = \frac{2m_p}{m_r}$$

Solve for m_p:

$$\left|\frac{v_p - v_{ri}}{v_p - v_{rf}}\right| = e^{2m_p/m_r}$$

$$m_p = \frac{m_r}{2} \ln\left|\frac{v_p - v_{ri}}{v_p - v_{rf}}\right| \tag{6}$$

A.4 Interpret The Absolute Value

The absolute value accounts for the direction of velocities: - If $v_p > v_{ri}$ and $v_p > v_{rf}$, then $v_p - v_{ri}$ and $v_p - v_{rf}$ are positive, so:

$$m_p = \frac{m_r}{2} \ln\left(\frac{v_p - v_{ri}}{v_p - v_{rf}}\right)$$

A.5 Compute PuffSat To Rocket Mass Ratio, With A Fudge Factor For Real World Losses

We can then solve for the total PuffSat to rocket ratio, with a fudge factor e between 0 and 1 to account for the coefficient of restitution and imperfect spread of gaseous volatiles off the pusher plate. Let's naively assume this fudge factor is the same for each collision even though in practice it would likely vary as the relative velocity of the PuffSats and the rocket change.

$$\frac{m_r}{m_p} = \frac{2e}{ln(\frac{v_p - v_{ri}}{v_p - v_{rf}})} \tag{7}$$

B Deriving Effective Exhaust Velocity for Idealized 100% Efficient Prograde/Retrograde PuffSat Collision Rocket Thrust

Suppose a retrograde PuffSat with m_{rp} and a prograde PuffSat with m_{pp} collide in a pulsed rocket propulsion chamber, as depicted in Table 3. We want to find the maximum exhaust velocity v_e for the prograde rocket when engine efficiency is 100% and we expel all the combined gas behind us (in the retrograde direction). For simplicity we say

$$m_{rp} + m_{pp} = 1 \tag{8}$$

Each PuffSat has velocity v so the retrograde PuffSat has velocity $2v$ in the reference frame of the prograde PuffSat. In the prograde reference frame, kinetic energy is

$$E = \frac{m_{rp}(2v)^2}{2} = 2m_{rp}v^2 \tag{9}$$

Let v_g be gas exhaust velocity expelled from the rocket, and assume this mass is infinitesimal compared to the entire prograde payload. Applying mass from Equation 8 and kinetic energy from Equation 9, we have

$$2m_{rp}v^2 = \frac{v_g^2}{2} \tag{10}$$

and solving for v_g we get

$$v_g = \sqrt{4v^2 m_{rp}} = 2v\sqrt{m_{rp}} \tag{11}$$

Total momentum change is

$$(m_{rp} + m_{pp})v_g - 2vm_{rp} = v_g - 2vm_{rp} = 2v(\sqrt{m_{rp}} - m_{rp})$$

Using calculus, its straightforward to show we maximize exhaust velocity when

$$m_{rp} = \frac{1}{4}, v_g = v, v_e = \frac{v}{2} \tag{12}$$

C AI And Citations Transparency Acknowledgement

The ideas in this paper come from the author. However, some artwork was created with AI tools. AI tools also helped suggest writing improvements. It's possible the AI training might regurgitate writing from other authors. Please inform me if you see this, so I can add citations.

More generally, I am not an expert in the field, so it's possible I failed to cite prior work for some of the ideas presented. Please let me know if I inadvertently present any novel concepts that are actually from others, so I may cite relevant work. Note that I am also less rigorous with citations to my own blog then with other writings.

The author previously worked at Netflix, which produces content related to some popular culture titles referenced in the paper. However, I am no longer employed there and am not a major investor. The author's blog is not monetized and is primarily to further explain this paper's ideas. In short, I do not believe I have any financial conflicts of interest at the present time.

D Copyright

References

[1] Aaron Paz. *Technology Assessment for Producing Propellant From Lunar Water*. https://ntrs.nasa.gov/citations/20230010039. Access: 2025-06-16. 2025.

[2] Isaac Arthur. *MegaStructures and Extreme Engineering Playlist*. https://www.youtube.com/playlist?list=PLIIOUpOge0Lv1MZSclU_dYYEJ73zt8UpR. Accessed: 2025-07-02. 2025.

[3] Julia Briden et al. *Constraint-Informed Learning for Warm Starting Trajectory Optimization*. https://arxiv.org/abs/2312.14336. Preprint on ResearchGate. 2023. DOI: 10.13140/RG.2.2.35597.92646.

[4] Charles J Call and Ralph W Moir. "A novel fusion power concept based on molten-salt technology: Pacer revisited". In: *Nuclear science and engineering* 104.4 (1990), pp. 364–373.

[5] Casey Dreier. *How much does the James Webb Space Telescope cost?* https://www.planetary.org/articles/cost-of-the-jwst. Accessed: 2025-06-01. 2021.

[6] Chris Bataille. *Decarbonizing Steel and Cement*. https://www.energypolicy.columbia.edu/decarbonizing-steel-and-cement/. Accessed: 2025-06-30. 2023.

[7] James S.A. Corey. *Drive*. The Expanse Short Fiction. Prequel short story to The Expanse series, detailing the invention of the Epstein drive. Orbit, 2012.

[8] Michael Crichton. *Jurassic Park*. Knopf, 1990.

[9] Chris Daehnick. *Space Launch - Are we heading for oversupply or a shortfall*. https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-launch-are-we-heading-for-oversupply-or-a-shortfall. Accessed: 2025-06-01. 2021.

[10] Dirk Schulze Makuch. *Ancient Fossils on the Moon?* https://www.smithsonianmag.com/air-space-magazine/ancient-fossils-moon-180959356/. Accesses: 2025-06-10. 2016.

[11] Breakthrough Energy. *Five Questions To Ask In Every Climate Conversation*. https://www.breakthroughenergy.org/newsroom/articles/five-questions-to-ask-in-every-climate-conversation/. Accessed: 2025-07-05. 2021.

[12] European Space Agency. *Helium-3 mining on the lunar surface*. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Energy/Helium-3_mining_on_the_lunar_surface. 2025.

[13] European Space Agency. *Proba-3*. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Proba-3. Accessed: 2025-06-19. 2024.

[14] Bill Gates. *How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need*. New York: Alfred A. Knopf, 2021.

[15] Tommaso Guffanti et al. *Autonomous Guidance Navigation and Control of the VISORS Formation-Flying Mission*. https://arxiv.org/abs/2309.16698. 2023.

[16] Tommaso Guffanti et al. *Transformers for Trajectory Optimization with Application to Spacecraft Rendezvous*. https://arxiv.org/abs/2310.13831. 2024. arXiv: 2310.13831 [cs.RO].

[17] Jeremy Bernstein. *Reflections on Project Orion*. https://inference-review.com/article/reflections-on-project-orion. Accessed: 2024-09-06. 2020.

[18] Joey Roulette. *What Is Starship? SpaceX Builds Its Next-Generation Rocket*. Accessed: 2024-09-07. 2022.

[19] Jordin T Kare. "SailBeam: Space propulsion by macroscopic sail-type projectiles". In: *AIP Conference Proceedings*. Vol. 552. 1. American Institute of Physics. 2001, pp. 402–406.

[20] Seth Katz. *aim_is_all_you_need*. Aug. 2025. DOI: 10.5281/zenodo.16718455. URL: https://github.com/katzseth22202/aim_is_all_you_need.

[21] Seth Katz. *Fantastic Platform Ultimately Targeting Incoming Nukes*. https://aim-is-all-you-need.blogspot.com/2024/03/fantastic-platform-ultimately-targeting.html. Blog post on Aim is All You Need. Mar. 2024.

[22] Keith Lofstrom. *The Launch Loop - A low cost earth-to-high-orbit launch system*. https://arc.aiaa.org/doi/10.2514/6.1985-1368. 2012.

[23] Obi-Wan Kenobi. *That's no moon*. Spoken line in *Star Wars: Episode IV – A New Hope*. Directed by George Lucas. Lucasfilm Ltd. 1977. URL: https://www.imdb.com/title/tt0076759/.

[24] Kevin Derby. https://aviationa2z.com/index.php/2024/11/15/elon-musk-starship-fly-you-anywhere-in-world-under-hour/. Accessed: 2025-06-10. 2024.

[25] klookei (User Name). *moon_preview_1*. https://opengameart.org/content/the-moon-no-background. Accessed 2025-06-15. 2024.

[26] Remi Lam et al. "Learning skillful medium-range global weather forecasting". In: *Science* 382.6677 (2023), pp. 1416–1421.

[27] Cixin Liu and Ken (Translator) Liu. *The Three-Body Problem*. First U. S. edition. New York: Tor Books, 2014.

[28] Giuseppe Longo. "The Tunguska event". In: *Comet/Asteroid Impacts and Human Society: An Interdisciplinary Approach*. Springer, 2007, pp. 303–330.

[29] Preyansh Malaviya et al. "A comprehensive review on space solar power satellite: an idiosyncratic approach". In: *Environmental Science and Pollution Research* 29.28 (2022), pp. 42476–42492.

[30] Marc Andreessen. *Why Software Is Eating the World*. https://a16z.com/why-software-is-eating-the-world/. Aug. 2011.

[31] Mark Hilburger. *IPex Pilot Excavator*. https://www.nasa.gov/isru-pilot-excavator/. Accessed: 2025-06-06. 2020.

[32] Lockheed Martin. *Golden Dome for America*. https://www.lockheedmartin.com/en-us/capabilities/missile-defense/golden-dome-missile-defense.html. Accessed: July 4, 2025. Mar. 2025.

[33] DJ McComas et al. "Solar probe: Report of the science and technology definition team". In: *NASA Technical Memorandum* 212786 (2005).

[34] David S McKay et al. "The lunar regolith". In: *Lunar sourcebook* 567 (1991), pp. 285–356.

[35] William D Metz. "Energy: Washington Gets a New Proposal for Using H-Bombs". In: *Science* 188.4184 (1975), pp. 136–137.

[36] Pete "Maverick" Mitchell and Nick "Goose" Bradshaw. *I feel the need—the need for speed!* Spoken line in the film *Top Gun*. Directed by Tony Scott. Paramount Pictures. 1986. URL: https://www.imdb.com/title/tt0092099/.

[37] NASA. *James Webb Space Telescope*. https://science.nasa.gov/mission/webb/. Accessed: 2025-06-01. 2021.

[38] Gerald D Nordley. "Interstellar Probes Propelled by Self-steering Momentum Transfer Particles". In: *Energy* 1.1 (2001), pp. 2–3.

[39] OpenAI. *ChatGPT*. https://chatgpt.com/. Accessed: 2024-09-06. 2024.

[40] Bryan Palaszewski. "Atmospheric mining in the outer solar system". In: *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2005, p. 4319.

[41] A. T. Jr. Peaslee, ed. *Proceedings of the Impact Fusion Workshop*. Conference held July 10-12, 1979. Los Alamos, NM, USA: Los Alamos Scientific Laboratory, Aug. 1979. URL: https://www.osti.gov/biblio/5841385 (visited on 07/02/2025).

[42] Olga Popova. "Chelyabinsk meteorite". In: *Oxford Research Encyclopedia of Planetary Science*. Oxford Research Encyclopedia, 2021.

[43] Guy Revach et al. "KalmanNet: Neural network aided Kalman filtering for partially known dynamics". In: *IEEE Transactions on Signal Processing* 70 (2022), pp. 1532–1547.

[44] Hannah Ritchie, Pablo Rosado, and Max Roser. "Energy Production and Consumption". In: *Our World in Data* (2020). https://ourworldindata.org/energy-production-consumption.

[45] Seth Katz. *Aim is All You Need*. https://aim-is-all-you-need.blogspot.com/. Accessed: 2024-09-06. 2024.

[46] Tough SF. *The Nuclear Spear - Casaba Howitzer*. https://medium.com/@toughsfmatterbeam/the-nuclear-spear-casaba-howitzer-88dc0ba7dff2. Accessed 07-01-2025. 2018.

[47] CE Singer et al. *Interstellar propulsion using a pellet stream for momentum transfer*. Tech. rep. Princeton Univ., NJ (USA). Plasma Physics Lab, 1979.

[48] SpaceX. *SpaceX Starship*. https://www.spacex.com/vehicles/starship/. Accessed: 2024-09-06. 2024.

[49] Star Trek. *Star Trek*. https://www.startrek.com/. Accessed: 2024-09-06. 2024.

[50] Stephen Clark. *Elon Musk wants to move fast with SpaceX's Starship*. https://spaceflightnow.com/2019/09/29/elon-musk-wants-to-move-fast-with-spacexs-starship. Accessed: 2024-09-06. 2019.

[51] *Superman*. Feature film starring David Corenswet, Rachel Brosnahan, and Nicholas Hoult. Produced by DC Studios and distributed by Warner Bros. Pictures. July 2025. URL: https://www.imdb.com/title/tt5950044/.

[52] TED-Ed. *How close can we actually get to the Sun?* http://www.youtube.com/watch?v=tekiHV-e8Uw. Accessed: 2025-07-05. June 2025.

[53] United Nations. *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html. Opened for signature in London, Moscow, and Washington, D.C., on 27 January 1967. Entered into force on 10 October 1967. Jan. 1967.

[54] Ashish Vaswani et al. *Attention Is All You Need*. https://arxiv.org/abs/1706.03762. 2023. arXiv: 1706.03762 [cs.CL].

[55] Eric A Wan and Rudolph Van Der Merwe. "The unscented Kalman filter for nonlinear estimation". In: *Proceedings of the IEEE 2000 adaptive systems for signal processing, communications, and control symposium (Cat. No. 00EX373)*. Ieee. 2000, pp. 153–158.

[56] H. G. Wells. *The World Set Free: A Story of Mankind*. Macmillan, 1914.

[57] Wiki Commons. *Terra.png*. https://commons.wikimedia.org/wiki/File:Terra.png. Accessed: 2025-06-15. 2025.

[58] Wikipedia. *Death Star*. https://en.wikipedia.org/wiki/Death_Star. Accessed: 2025-06-20. 2025.

[59] Wikipedia. *Embraer E170*. https://en.wikipedia.org/wiki/Embraer_E-Jet_family. Accessed: 2025-06-10. 2025.

[60] Wikipedia. *Little Boy*. https://en.wikipedia.org/wiki/Little_Boy. Accessed: 2025-07-01. 2025.

[61] Wikipedia. *Oberth effect*. https://en.wikipedia.org/wiki/Oberth_effect. Accessed: 2024-09-27. 2024.

[62] Wikipedia. *Project Orion (Nuclear pulse propulsion)*. https://en.wikipedia.org/wiki/Project_Orion_(nuclear_propulsion). Accessed: 2024-09-06. 2024.

[63] Wikipedia. *Space Shuttle Program*. https://en.wikipedia.org/wiki/Space_Shuttle_program. Accessed: 2025-06-10. 2025.

[64] Wikipedia. *Space solar power*. https://en.wikipedia.org/wiki/Space-based_solar_power. Accessed: 2025-07-01. 2025.

[65] Wikipedia. *SpaceX Super Heavy*. https://en.wikipedia.org/wiki/SpaceX_Super_Heavy. Accessed:2025-07-02. 2025.

[66] Wikipedia contributors. *Phoebe (moon)*. https://en.wikipedia.org/wiki/Phoebe_(moon). Accessed: 2025-07-01. 2025.

[67] XAI. *x.ai*. https://x.ai/. Accessed: 2025-06-15. 2025.

[68] Alessandro Zavoli and Lorenzo Federici. "Reinforcement learning for robust trajectory design of interplanetary missions". In: *Journal of Guidance, Control, and Dynamics* 44.8 (2021), pp. 1440–1453.