Astra Drive: Particle-based Propulsion System

Jae Un Kim
Department of Physics, Ajou University, Republic of Korea
wodns7907@ajou.ac.kr

Abstract

Conventional propulsion systems are fundamentally constrained by the Tsiolkovsky rocket equation, which requires exponential propellant mass growth to achieve high terminal speeds. Even advanced electric propulsion and ion thrusters, while highly efficient, remain limited by mass ratios and onboard propellant storage.

This work develops a full theoretical formulation of the *Astra Drive*, a near–future relativistic particle–packet propulsion system in which multiple compact particle accelerators mounted on the rear of a spacecraft continuously eject relativistic ion packets (or proton packets), gaining momentum from continuous reaction.

The energy source is assumed to be a high-power near–future-generation system in the few-hundred-megawatt class. This decouples thrust generation from chemical propellant mass and removes the Tsiolkovsky constraint.

We present: (i) a relativistic momentum–thrust framework, (ii) packetized emission dynamics at MHz–tens-of-MHz repetition rates, (iii) a quantitative thrust model using near-future achievable particle accelerator power (80 MW per unit, 5 units, $P_{\mathrm{tot}} = 400$ MW), (iv) long-duration performance for a 5-unit particle accelerator configuration (the number of units is not fixed), (v) mission-scale predictions showing that a velocity increment of $\Delta v \sim 8.4 \times 10^4$ m/s (about 84 km/s, $2.8 \times 10^{-4}c$) is reachable within one year of continuous operation for an 800 kg spacecraft.

We emphasize that the particle species (protons or Helium ion) and particle accelerator parameters are placeholders and can be modified in future implementations. (The performance values presented in this study correspond to a conservative baseline configuration of 400 MW of electrical power and an 800 kg spacecraft mass. Any increase in available power or further structural mass reduction would proportionally enhance the achievable v within the same propulsion framework.)

1 Introduction

Achieving high spacecraft velocities remains one of the grand engineering obstacles of modern astrophysics. Chemical rockets are fundamentally constrained by the Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right), \tag{1}$$

where v_e is exhaust velocity and m_0/m_f is the mass ratio. Ion propulsion systems increase v_e but are still bound to carrying propellant.

A propulsion system that removes the onboard propellant requirement would fundamentally bypass these limits. The Astra Drive proposes such a system: ejecting high–velocity particle packets produced by compact particle accelerators rather than stored fuel.

1.1 Conceptual Motivation

The Astra Drive is based on four observations:

1. Relativistic particles (protons or ions) can be accelerated efficiently using compact RF/laser hybrid particle accelerators.
2. Momentum transfer from a continuous packet stream can produce sustained thrust independent of chemical propellant.
3. Near-future fusion or high-density power systems may provide electrical power in the $\mathcal{O}(10^2)$ MW range.
4. Long-duration acceleration (months to years) allows cumulative speed growth otherwise impossible.

2 Operating Principle

The Astra Drive generates thrust by expelling ultra-relativistic particle packets produced by a compact particle accelerator installed at the rear section of the spacecraft. Unlike chemical rockets, the system does not rely on propellant mass carried in large quantities. Instead, a small onboard supply of particles is repeatedly accelerated to near-light-speed velocities and ejected directionally, producing momentum transfer according to relativistic conservation laws.

2.1 Particle Injection and Acceleration

A small reservoir of charged particles (protons or light ions) is injected into a compact particle accelerator. The accelerator employs hybrid RF–laser fields to produce continuous micro-bunching and high-gradient acceleration. Each particle packet achieves velocities in the range:

$$v_p = 0.90c,$$

depending on the available onboard power and accelerator efficiency.

The packet production rate is denoted by R (packets per second). A near-future realistic achievable range in compact accelerators lies in the MHz regime:

$$R \sim 10^7 \text{ packets/s.}$$

In the performance estimates below, the thrust is expressed in terms of total accelerator power, so the detailed choice of R and particles per packet is absorbed into the power budget.

2.2 Relativistic Momentum Ejection

Each accelerated packet has relativistic momentum:

$$p_p = \gamma m_p v_p, \qquad \gamma = \frac{1}{\sqrt{1 - (v_p/c)^2}},$$

where m_p is the particle mass.

As the packet exits the nozzle in a collimated beam, the reaction generates thrust:

$$F = R\, p_p.$$

2.3 Continuous Thrust Buildup

Because the Astra Drive does not consume propellant mass in the conventional sense, thrust can be applied for months or years. The spacecraft mass M_s remains nearly constant, enabling long-duration acceleration:

$$a(t) = \frac{F}{M_s}.$$

Even a small thrust accumulated over long durations results in significant velocity growth:

$$v(t) = \int_0^t a(\tau)\, d\tau.$$

2.4 Long-Duration Relativistic Cruise

For a spacecraft of mass $M_s = 800\,\text{kg}$ and a total accelerator power supply of $P_{\text{tot}} = 400$ MW (5 units $\times\, 80$ MW), the Astra Drive can reach, under constant-thrust approximation:

$$v_{1\text{ month}} \approx 7 \times 10^3\,\text{m/s} \approx 7\,\text{km/s},$$
$$v_{1\text{ year}} \approx 8.4 \times 10^4\,\text{m/s} \approx 84\,\text{km/s} \approx 2.8 \times 10^{-4}c.$$

These velocities already exceed typical chemical escape velocities and are obtained without the exponential fuel penalty of chemical or ion engines, while remaining within a high but conceivable near-future power budget.

2.5 Key Advantage: Escape From the Rocket Equation

The Astra Drive circumvents the traditional Tsiolkovsky rocket equation because thrust comes from accelerating a tiny mass repeatedly instead of ejecting large propellant mass:

$$\Delta v_{\text{Astra}} \propto t, \qquad \Delta v_{\text{rocket}} \propto \ln(m_0/m_f).$$

Thus, the system provides sustained, scalable, and long-duration relativistic acceleration unattainable with current chemical propulsion methods.

3 Relativistic Momentum–Thrust Formalism

A packet of mass m_p emitted at relativistic velocity v_p has momentum

$$p_p = \gamma m_p v_p, \tag{2}$$

where

$$\gamma = \frac{1}{\sqrt{1 - v_p^2/c^2}}. \tag{3}$$

If packets are emitted at frequency f (packets/s), the average thrust is

$$F = f\,\gamma m_p v_p. \tag{4}$$

Over duration T:

$$\Delta v = \frac{F}{M_s} T, \tag{5}$$

where M_s is spacecraft mass.

3.1 Power Constraint

Accelerating one packet to kinetic energy

$$E_k = (\gamma - 1) m_p c^2 \tag{6}$$

requires beam power

$$P = f E_k = f(\gamma - 1) m_p c^2. \tag{7}$$

For fixed particle accelerator power P_{acc}, we obtain

$$f = \frac{P_{\text{acc}}}{(\gamma - 1) m_p c^2}. \tag{8}$$

Substituting into F:

$$F = \frac{P_{\text{acc}}}{c^2} \frac{\gamma v_p}{(\gamma - 1)}. \tag{9}$$

This provides a closed-form thrust expression determined solely by power and exhaust velocity, and is the basis for the numerical estimates below.

4 System Architecture

4.1 Choice of Particle Species

In this paper we consider two feasible particle species for near–future micro-accelerator propulsion:

Species: Helium ion (He^+ / He^{2+})

- Justification:
  - moderate charge-to-mass ratio
  - higher momentum per ion packet at relativistic velocity
  - reduced beam divergence due to larger mass
  - stable acceleration in hybrid RF/laser micro-accelerators
  - Helium ions are compatible with existing laser–wakefield and RF acceleration experiments, enabling near-term experimental validation.
- Helium ions may operate in mixed-ion mode with protons to optimize thrust, beam stability, and energy efficiency.

Species: Proton (p^+)

- Justification:
  - high charge-to-mass ratio
  - stable acceleration
  - rich experimental data
  - compatible with RF/laser hybrid micro-particle accelerators
- Future implementations may substitute electrons, muons, deuterons, or mixed packets.

4.2 Particle Accelerators Configuration

We assume:

$$N = 5, \quad P_{\text{unit}} = 80\,\text{MW}, \quad P_{\text{tot}} = 400\,\text{MW}.$$

This lies within a high but conceptually near-future feasibility window based on advanced fusion-electric or superconducting power systems.

4.3 Emission Velocity

We adopt:

$$v_p = 0.90c$$

which corresponds to:

$$\gamma = 2.29.$$

5 Performance Estimation

5.1 Thrust Calculation

Using the power-limited thrust formula:

$$F = \frac{P_{\text{tot}}}{c^2} \frac{\gamma v_p}{(\gamma - 1)}.$$

For $v_p = 0.9c$, $\gamma = 2.29$ and $P_{\text{tot}} = 400 \times 10^6$ W:

$$\frac{\gamma v_p}{(\gamma - 1)c^2} = \frac{2.29 \times 0.9c}{1.29\, c^2} \approx 5.32 \times 10^{-9}\,\text{s/m}.$$

Thus,

$$F \approx 400 \times 10^6 \times 5.32 \times 10^{-9}\ \text{N} \approx 2.1\ \text{N}.$$

5.2 Acceleration

For a spacecraft mass $M_s = 800\,\text{kg}$:

$$a = \frac{F}{M_s} \approx \frac{2.1}{800}\ \text{m/s}^2 \approx 2.6 \times 10^{-3}\ \text{m/s}^2.$$

5.3 Velocity after One Year

With $T = 3.15 \times 10^7\,\text{s}$:

$$\Delta v = aT \approx 2.66 \times 10^{-3}\,\text{m/s}^2 \times 3.15 \times 10^7\,\text{s} \approx 8.4 \times 10^4\ \text{m/s} = 83.9\ \text{km/s} \approx 2.8 \times 10^{-4} c.$$

6 Feasibility of Near-Term Implementation

The Astra Drive relies on relativistic particle exhaust generated by compact particle accelerators. Unlike large terrestrial accelerator facilities, recent advances allow high-gradient particle acceleration within meter-scale or even sub–meter-scale architectures. Therefore, the system does not require any new physics beyond established accelerator and plasma science, but it does assume high-density power systems in the few-hundred-megawatt class.

6.1 Compact Particle Accelerator Technologies

Three experimentally verified accelerator platforms support the near-term feasibility of the Astra Drive:

1. **RF Micro Particle Accelerators:** Modern RF-driven particle accelerator cavities achieve accelerating gradients of 20–50 MV/m in structures shorter than 50 cm. These compact particle accelerators can generate proton or ion packets with controlled kinetic energy suitable for momentum-transfer propulsion.

2. **Dielectric Laser Particle Acceleration (DLA):** Chip-scale particle accelerator structures using dielectric laser acceleration have demonstrated gradients exceeding 300 MV/m. Although current demonstrations use electrons, the verified physical mechanism shows that compact, high-gradient particle acceleration is experimentally feasible and rapidly advancing.

3. **Hybrid RF–Laser Particle Accelerators:** Several experimental programs combine RF pre-acceleration with laser-field post-acceleration to enable high repetition rates of particle packets in the kHz–MHz range. These repetition rates directly match Astra Drive's continuous packet exhaust propulsion model when scaled to higher average power.

6.2 Energy Requirements

Considering a realistic beam and conversion efficiency, a system of five compact particle accelerators operating at a combined electrical input of order

$$P_{\text{tot}} \simeq 400 \text{ MW}$$

can generate a sustained thrust of a few newtons, sufficient to accumulate a measurable $\Delta v \sim 10^2$ km/s over a one–year timescale. This requirement is above present spacecraft power levels but within the realm of advanced fusion-electric or large-scale nuclear systems.

6.3 Mass and Structural Considerations

A spacecraft mass of $M_s \approx 800$ kg is consistent with a small but power-dense platform including power source, thermal control and accelerator modules. The structural integration of several compact particle accelerators (< 1 m each) is feasible, and the reaction forces generated by the particle packet exhaust remain below the mechanical stresses encountered in existing high-power electric propulsion systems.

6.4 Power Source Specification

The total power requirement of 400 MW can be supplied by a compact fourth-generation nuclear fission reactor (advanced SMR class) operating in continuous mode. Modern high-temperature gas-cooled and sodium-cooled fast reactor designs already achieve power densities suitable for megawatt-to- gigawatt electric output in sub-10-ton configurations. A space-qualified SMR module would therefore provide the required electrical power for the multi-unit accelerator system without invoking speculative physics or far-future technologies.

6.5 Summary of Feasibility

The Astra Drive uses only established physics and leverages rapid advances in compact particle accelerator technology. As soon as high-repetition, high-average-power particle accelerator modules reach stable commercial form together with multi-hundred-megawatt space power systems, the Astra Drive becomes a practically deployable near-term propulsion architecture.

7 Discussion

7.1 Scientific Implications

The Astra Drive provides:

1. A propulsion method independent of large carried propellant mass.
2. A path to $\sim 10^2$ km/s-class cruise speeds under continuous multi-hundred-megawatt power.
3. A scalable architecture where performance grows approximately linearly with available power and mission duration.

7.2 Engineering Constraints

Key challenges include:

- waste-heat dissipation from high-power particle accelerators
- radiation shielding
- beam divergence minimization
- long-term particle accelerator stability and alignment

Despite these, no fundamental physics barrier prevents the system from operating in the regime analyzed here.

8 Conclusion

This paper formalizes the Astra Drive, a relativistic particle–packet propulsion system capable of achieving a velocity increment of order

$$\Delta v \sim 8.4 \times 10^4 \,\mathrm{m/s} \approx 84 \text{ km/s} \approx 2.8 \times 10^{-4} c$$

within one year using near-future particle accelerator and power technologies at the $\sim$ 400 MW level for an 800 kg spacecraft.

The system fundamentally bypasses the Tsiolkovsky equation by eliminating large propellant mass requirements and utilizing continuous ion-packet thrust.

Our analysis shows:

- 80 MW per particle accelerator unit is a plausible near-future assumption,
- a 5-unit configuration ($P_{\text{tot}} = 400$ MW) provides a concrete reference point for design and performance,
- relativistic packet emission at $0.9c$ combined with year-long operation is sufficient to reach $\mathcal{O}(10^2)$ km/s cruise speeds without any violation of energy–momentum conservation.

The Astra Drive represents a realistic path toward high-speed interplanetary and interstellar precursor missions within an advanced but physically consistent technological framework.

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