A Concept Design of Novel Dyson-Harrop CubeSat for Harvesting Energy from Solar Wind

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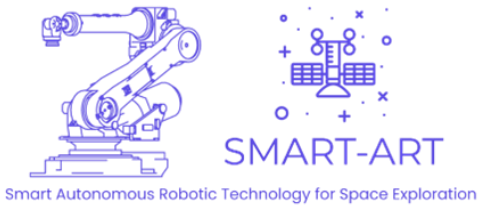

ICTiS 2024
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Background of Solar Power

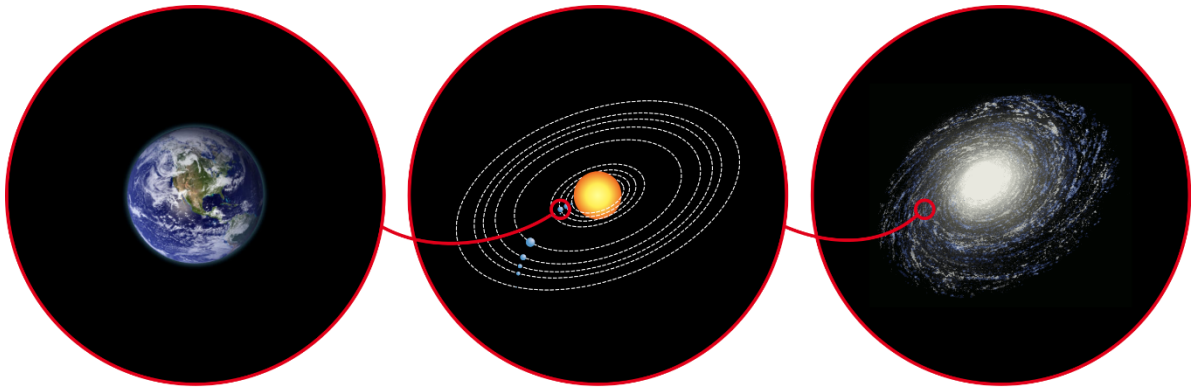
SMART-ART
Smart Autonomous Robotic Technology for Space Exploration

LASSONDE SCHOOL OF ENGINEERING | YORK UNIVERSITÉ UNIVERSITY

Kardashev scale

- **Type I civilization** (10^{16} W): Capable of accessing all the energy available on its planet and storing it for consumption.
- **Type II civilization** (10^{26} W): Can directly consume a star's energy, possibly using a Dyson sphere.
- **Type III civilization** (10^{36} W): Can capture all energy emitted by its galaxy, including from stars and black holes.

➢ Type 0.7 civilization approximately 2×10^{13}



Type I: 10^{16} W *Type II:* 10^{26} W *Type III:* 10^{36} W

Energy from Sun

Solar wind

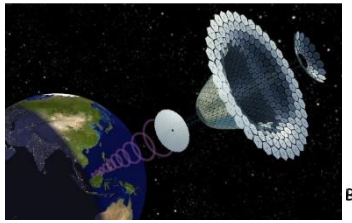
electrons, protons and alpha particles

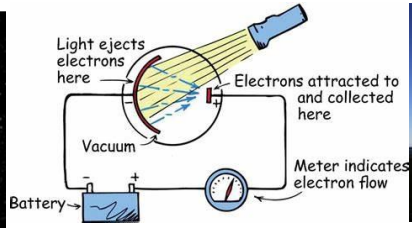
➢ photovoltaic effect (semiconductor)

➢ photoelectric effect (metal)

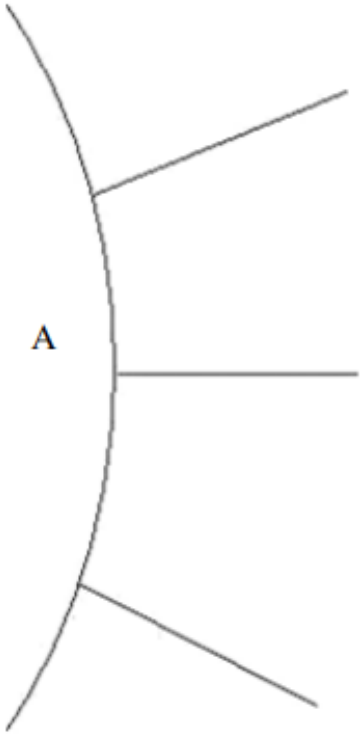
Solar thermal energy

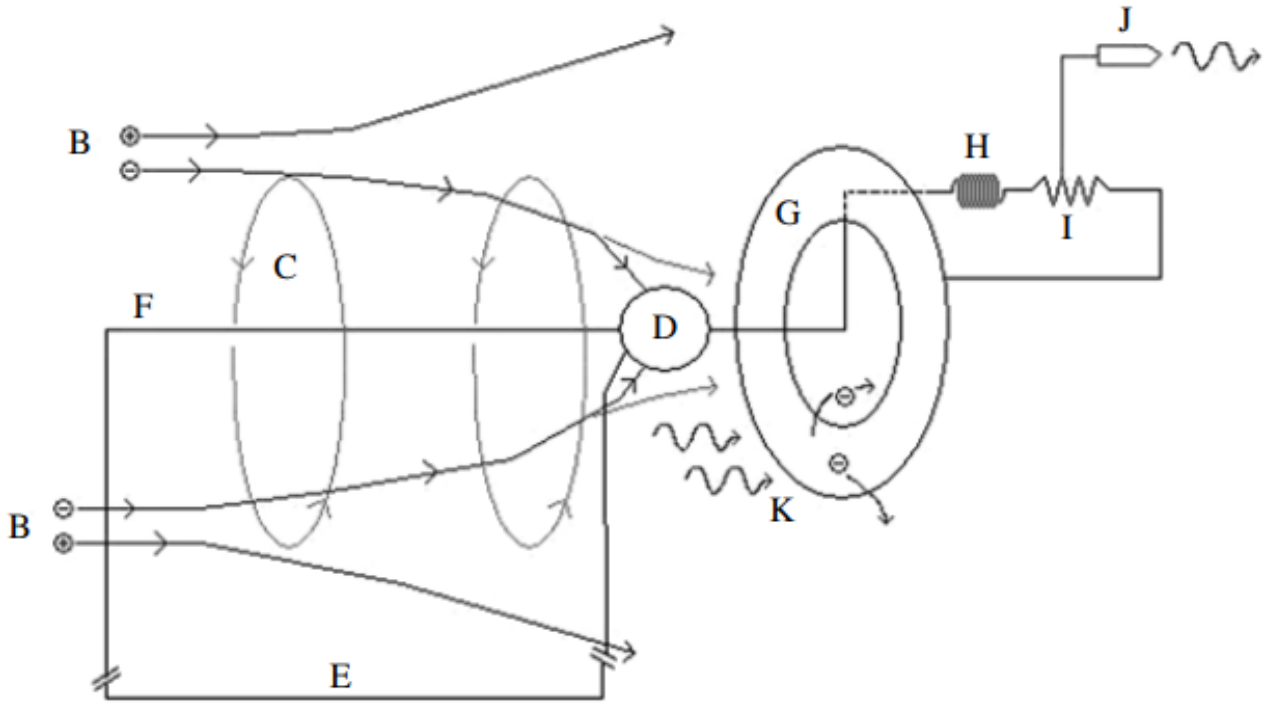
➢ Solar thermal collectors





Dyson-Harrop Satellite

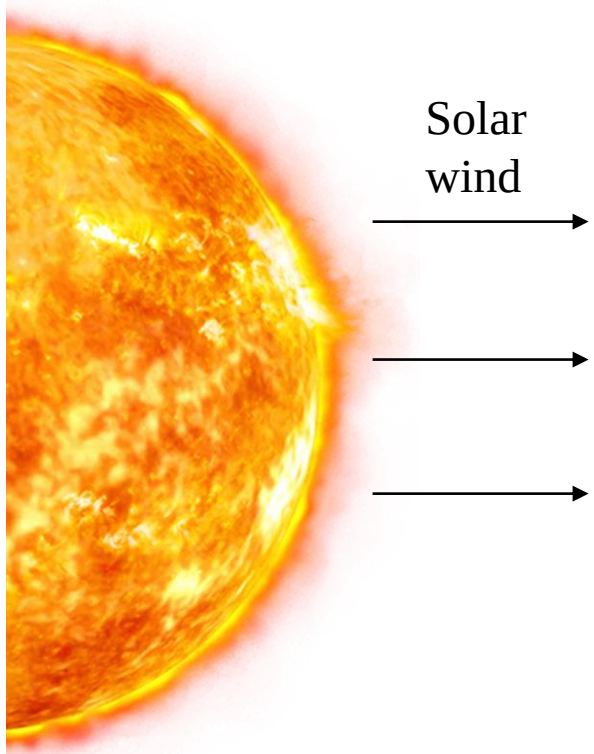




- **Areas for improvement:**
  - The size is too large, making it difficult to deploy;
  - The issue of attitude control has not been considered;
  - The energy transfer system has not been considered.

[1] Harrop, B. L., and Schulze-Makuch, D. "The Solar Wind Power Satellite as an alternative to a traditional Dyson Sphere and its implications for remote detection," International Journal of Astrobiology Vol. 9, No. 2, 2010, pp. 89-99.

Solar Wind Power (SWP) CubeSat



Solar wind

Electron

Energy system

Main satellite

Main wire

I

Receiver

Anti-static device

Magnetic field

Photons

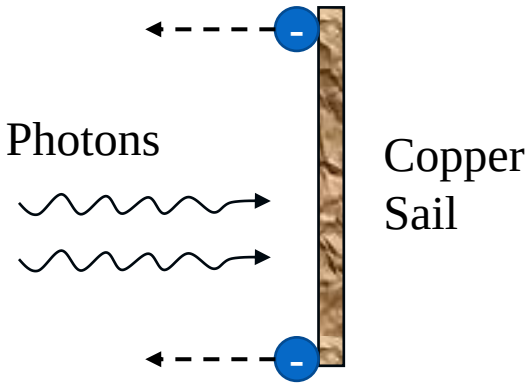
Sail

Pre-wire

145.60 kW

≈ 4 ISS Power

Photoelectric Effect



inner radius	$r_1 = 0.1\,\text{m}$
outer radius	$r_2 = 0.2\,\text{m}$
thickness	$\tau = 1\,\text{mm}$

Kinetic energy of the photoelectron

$$E_{\text{electron}} = E_{\text{photon}} - \Phi = \frac{1}{2} m_e v_e^2$$

where, kinetic energy of the photon

$$E_{\text{photon}} = h\nu$$

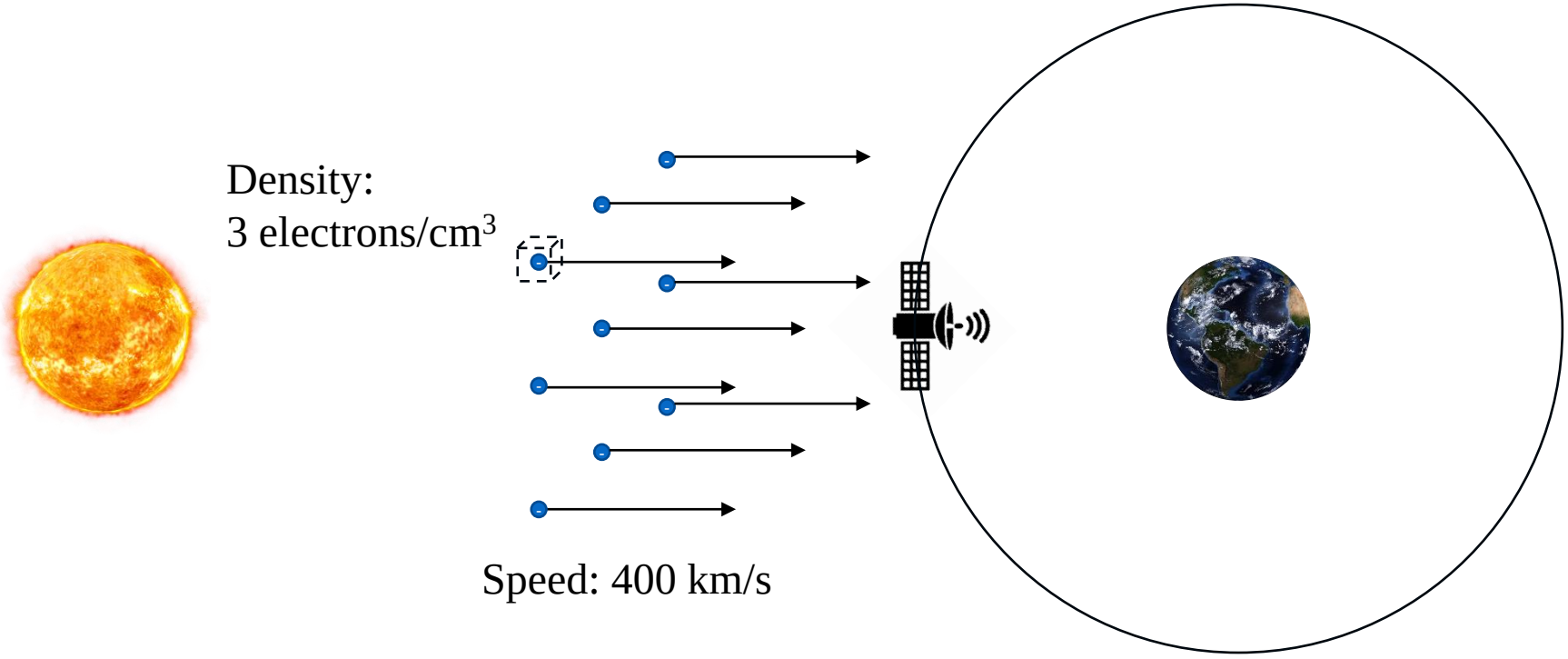
work function of copper

$$\Phi_{copper} = 7.53 \times 10^{-19}\ \text{J}$$

Planck constant

$$h = 6.626 \times 10^{-34}\ \text{J} \cdot \text{s}$$

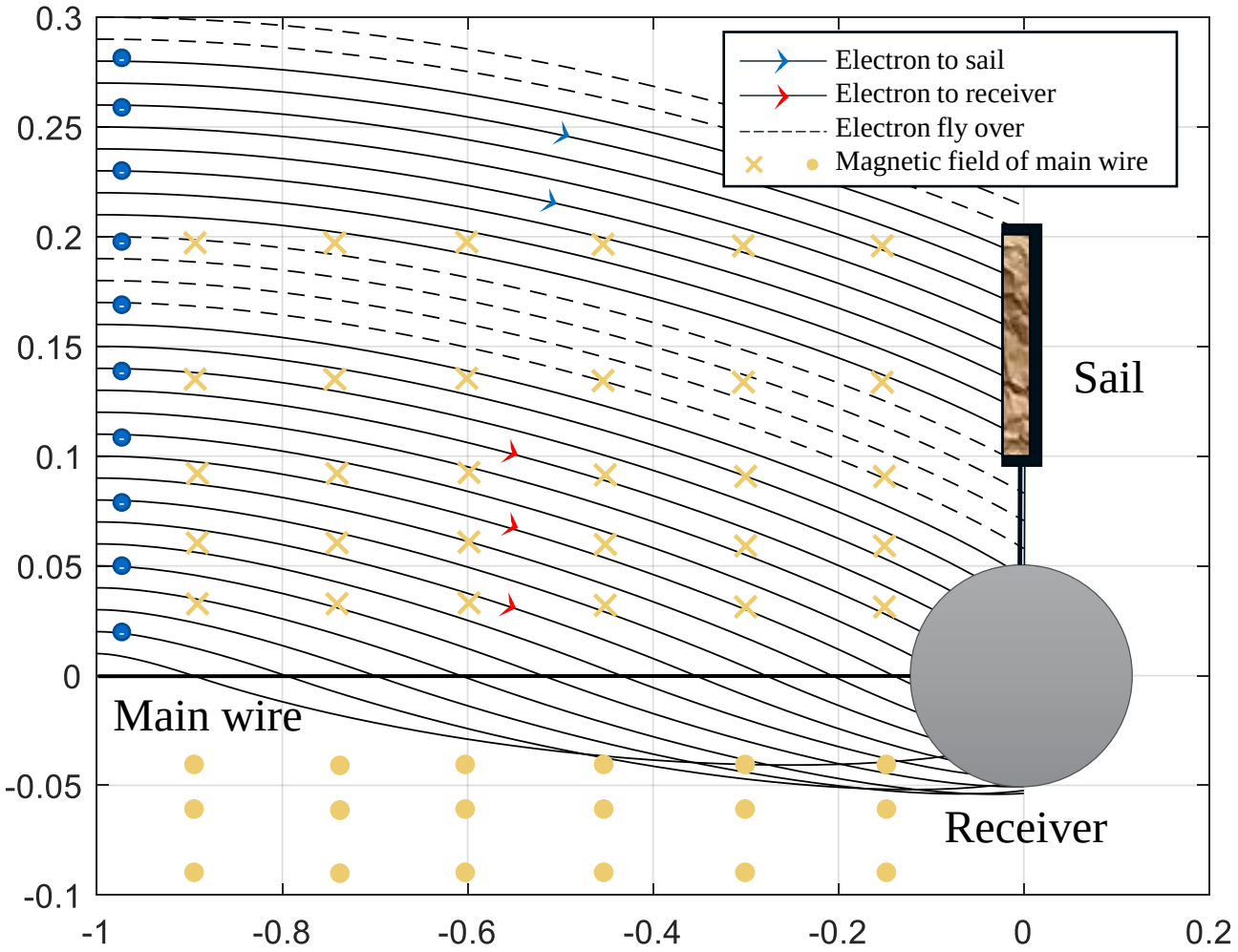
Solar Wind



Assumption 1: The speed of the plasma around SWP CubeSat is 400 km/s, with a density of 3 electrons per cubic centimeter. These free electrons are flying in parallel from the Sun towards the Earth.

- Real Time Solar Wind | NOAA / NWS Space Weather Prediction Center

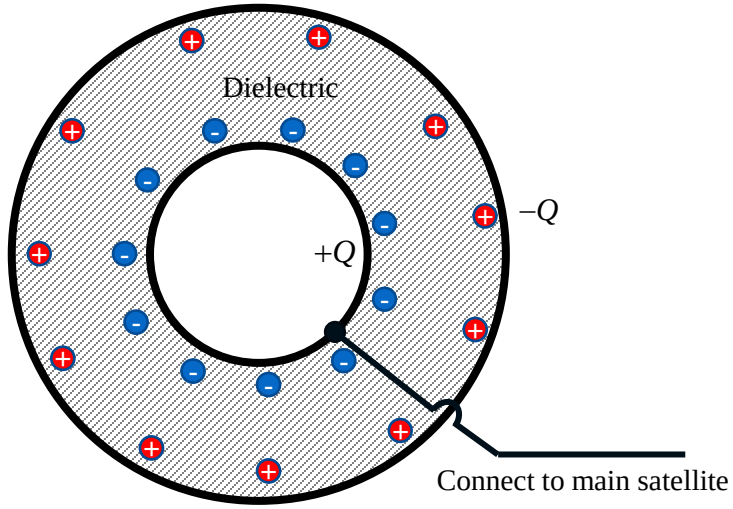
Electrons in Solar Wind



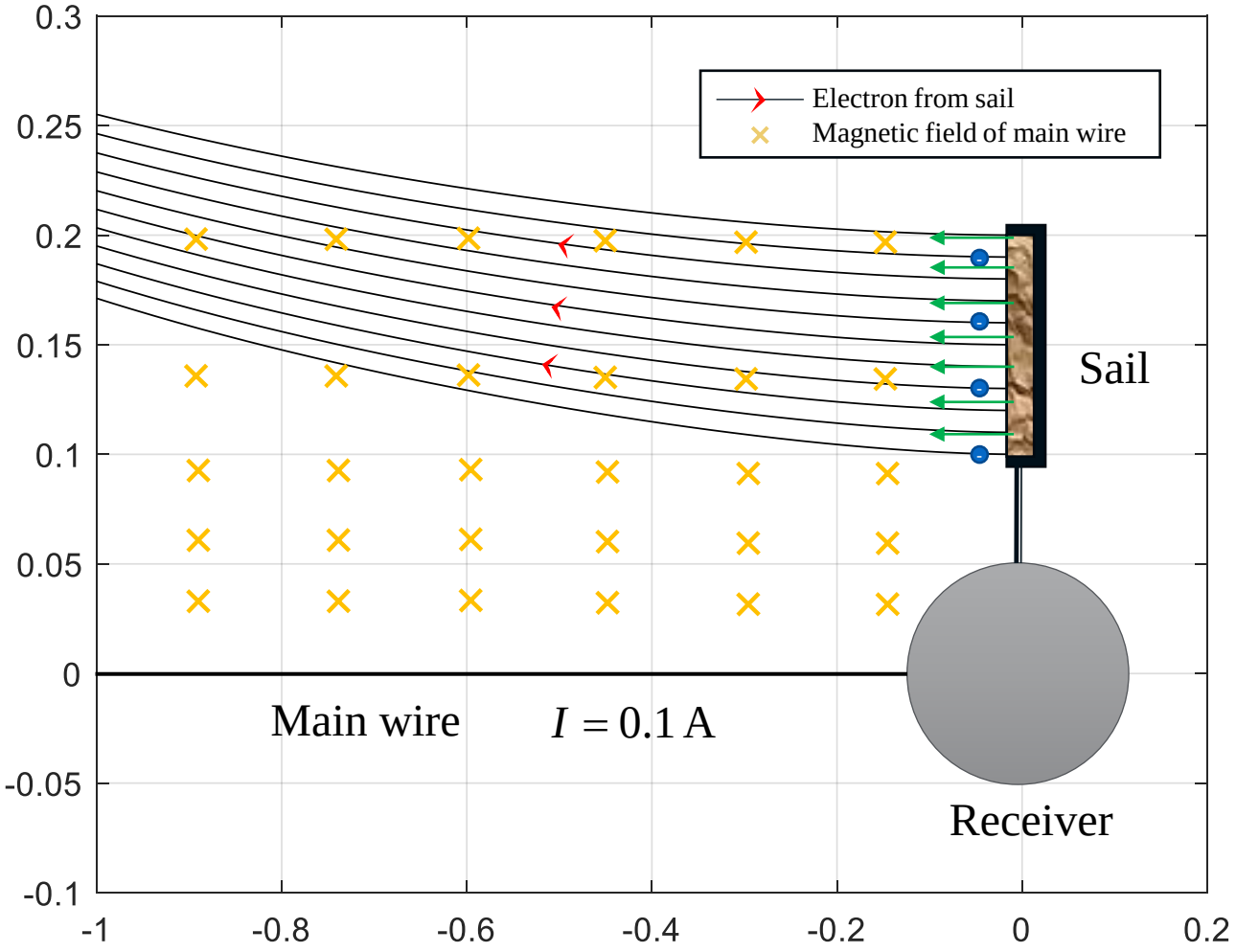
Assumption 2:
The magnetic field around the sail is only affected by the current in the main wire, ignoring the further pre-wire.

Assumption 3:
Solar wind particles hitting the sail maintain charge balance.

- The capacitor-style receiver



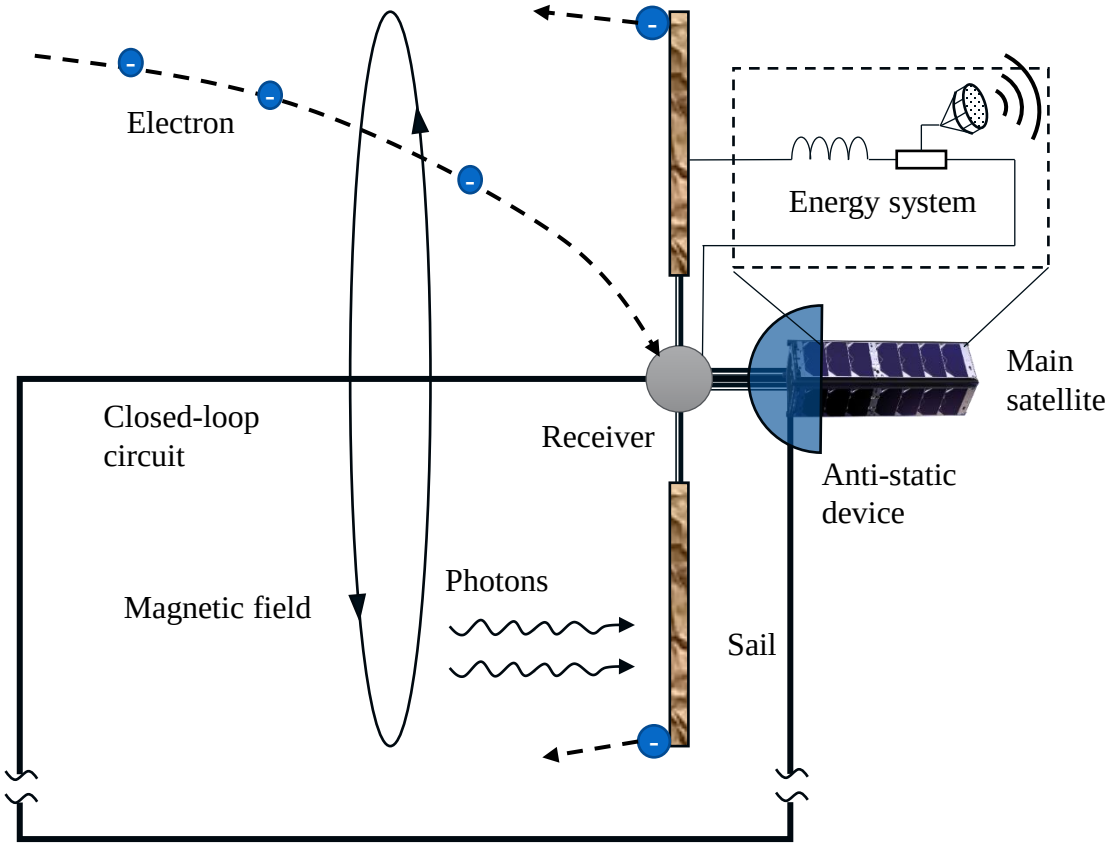
The Trajectory of Electrons



Assumption 4:
The back of the copper sail is wrapped with a high permeability material, and the electric field on the back side is shielded, so only the front side has an electric field perpendicular to the sail.

$$\begin{cases} v_0 = \sqrt{2\left(h\nu - \Phi\right)/m_e} \approx 7.2723\times10^5 \text{ m/s} \\ d = \frac{1}{2}\left(F_B/m_e\right)t^2 = qv_0\mu_0 It^2/2\pi m_e\left(r_2 - d\right) \\ t^2 = \left(v_0 m_e/qV_{\max}\right) = m_e v_0\left(r_{\min}/kQ_{\max}q\right) \\ \quad = m_e v_0\left(r_{\min}/kq\pi\rho_{\text{Cu}}\tau\left(r_2^2 - \left(r_2 - d\right)^2\right)\right) \end{cases}$$

Energy system



The escapable edge width $d \approx 1.8555\times10^{-8}$ m

$$V_{sail} = kQ_{\max} / r_1 \approx 2.85\times10^{10} \text{ V}$$

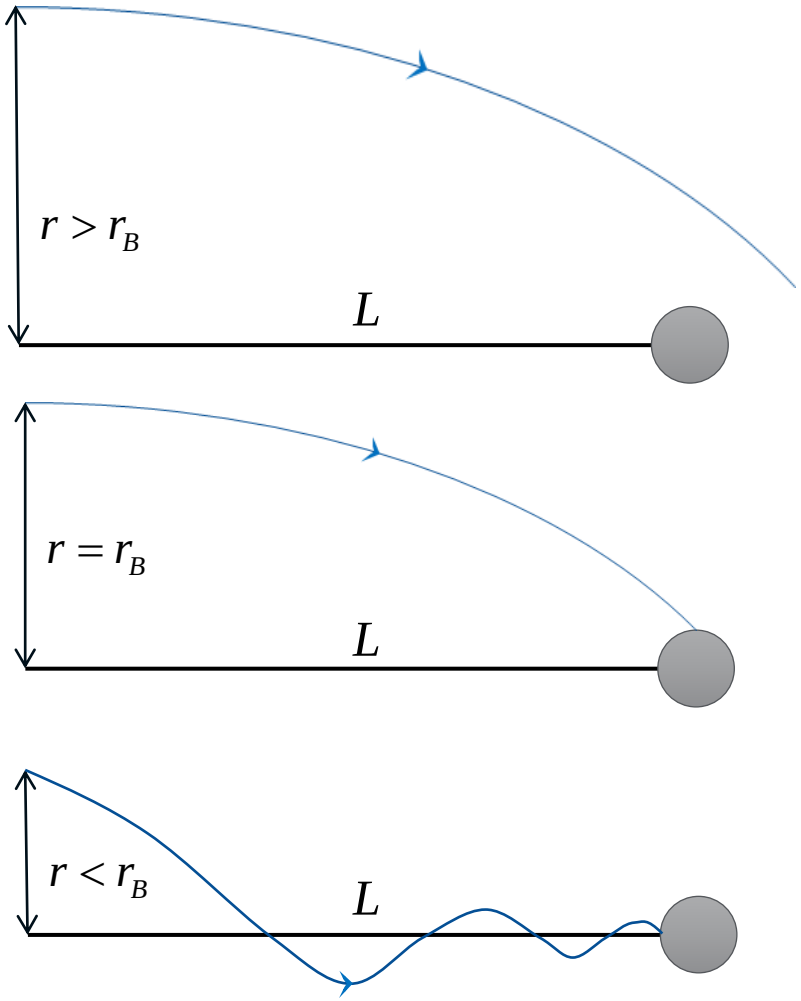
$$V_{\text{receiver}} = -1.6 \text{ V}$$

The current of the sail-receiver circuit depends on number of photons hitting the sail within one second

$$N_{photon} = \frac{I_{light}}{h\nu}\pi\left(2r_2 d - d^2\right) \approx 3.19\times10^{13}$$

$$I_{sail-receiver} = N_{photon}q = N_{electron}q \approx 5.19\times10^{-6} \text{ A}$$

Closed-loop circuit



- **Attractable electron radius:**

$$N_{electron} = N_{photon} \approx 3.19 \times 10^{13}$$

$$r_B > \sqrt{\frac{N_{electron}}{\pi v_e \rho_e}} \approx 2.9 \text{ m}$$

- **Main wire length:**

$$B = \frac{\mu_0 I}{2\pi r} \qquad I = 0.1 \text{ A} \qquad L > 40 \text{ m}$$

The joule-heating resistance is

$$R = \rho_R \cdot l \cdot C \cdot T / A \approx 9.8 \times 10^{-3} \ \Omega$$

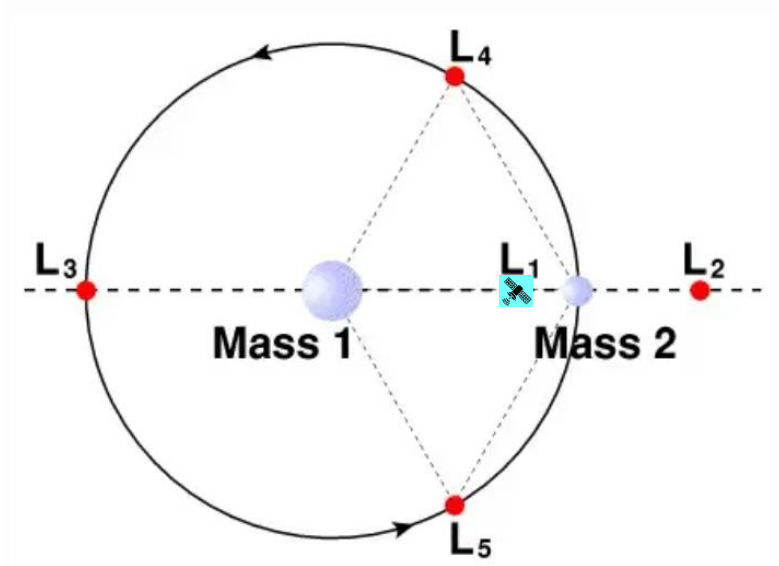
Economic Analysis

- **The total energy**

$$P_{Cube} = (V_{sail} - V_{receiver})I_{sail-receiver} - I^2R \approx 145.60\ \text{kW}$$

$$E_{Cube} = T_{Cube}P_{Cube} \approx 1.28\times10^7\ \text{kWh}$$

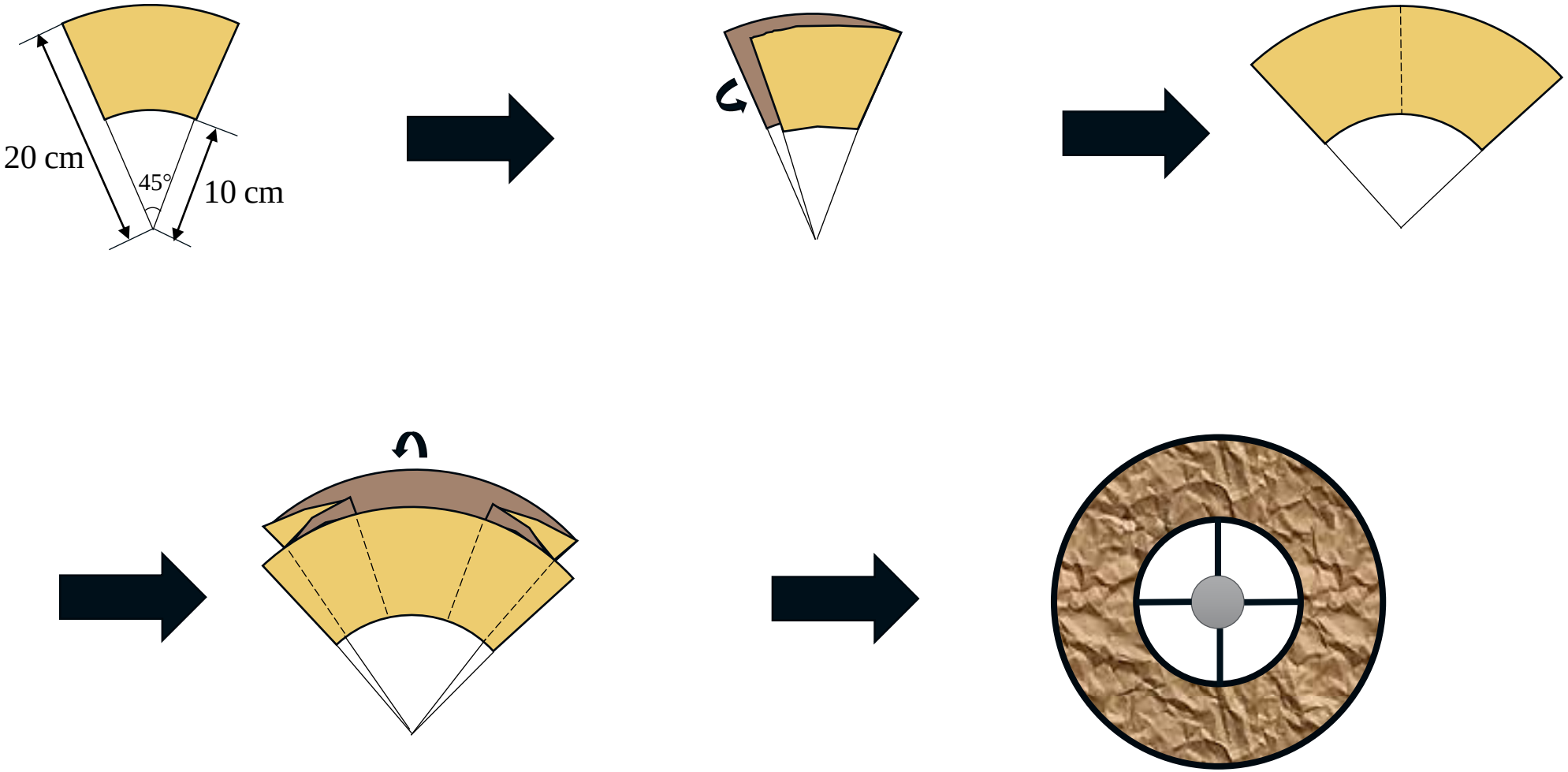
$$\text{LCOE}_{Cube} = \frac{E_{Cube}}{\$770,000} \approx \$0.06/\text{kWh}$$



Item	Unit price (US dollar)
The launch of a SWP CubeSat	270,000
The cost of a SWP CubeSat	500,000

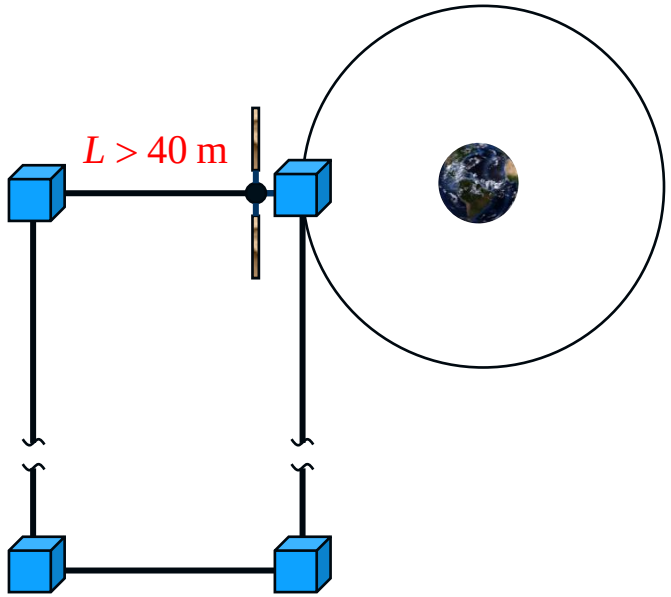
In a lifecycle of 10 years, the Levelized Cost of Electricity (LCOE) is **$0.06/kWh**, which is competitive with ground electricity ($0.05~0.50/kWh)

Sail deployment

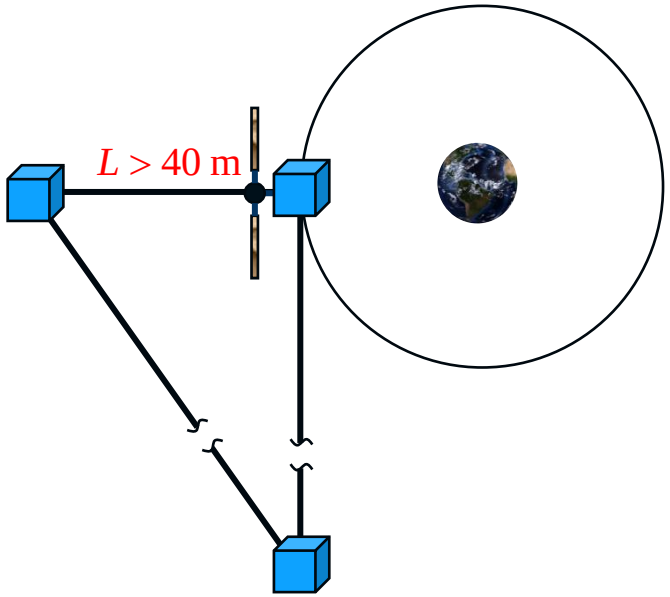


Closed-loop circuit deployment

- **Rectangular circuit**

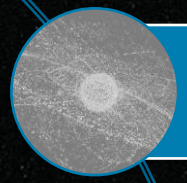


- **triangular circuit**

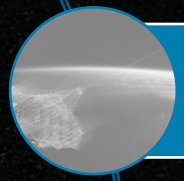


- The electrodynamic tether is subject to a continuous Lorentz force.
- Need to maintain orientation, cannot use spin stabilization.

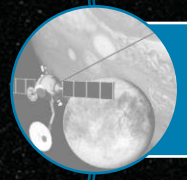
Conclusion



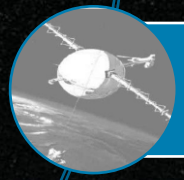
A CubeSat is designed to harness the energy of solar wind



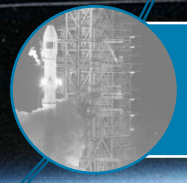
The total power (**145.6 kW**) is about equal to 4.5 ISS



Analyze its economic benefits, **LCOE=$0.06/kWh**



Design the ring-like sail's deployment mechanism



The new challenges of the closed-loop circuit attitude control

Future

- Experimental validation
- Dynamic analysis of system
- Attitude controller design


THANKS FOR LISTENING