First-ever Electric Sailing Workshop

ESA ESTEC, The Netherlands

May 19, 2008

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FINNISH METEOROLOGICAL INSTITUT

Introduction to electric sailing and its applications

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- ***Acknowledgements:*** Walter Schmidt, Markku Mäkelä, Mikhail Uspensky, et al. (FMI), Rami Vainio (Univ.Helsinki), Robert Hoyt (Tethers Unlimited Inc.), Giovanni Vulpetti (Rome), prof. Giancarlo Genta (Polytech.Torino), prof. Pierre Rochus, Yvan Stockman (Univ.Liege), Greger Thornell (ÅSTC, Uppsala), Fredrik Bruhn (ÅAC, Uppsala), prof. Viktor Trakhtengerts(*) (Nizhny Novgorod)

Contents

- What is electric sail
  - Solar wind for propulsion
  - Similarities with solar sail and ion thruster
- Present status
- Applications

Solar wind propulsion

- Magnetic sail (Zubrin and Andrews, 1990)
  - Not presently feasible (high-temp. superconductor needed)
  - Guiding is also an issue (bubble always drifts downstream)
  - FMI ESA study 2002-2003 (“eMPii”)
- Electric sail (Janhunen, 2004 onwards)
  - Physical idea 2004 (J. Prop. Power)
  - Technical implementation idea 2006 (patent application)
  - Concretisation of plans 2007 (tethers, s/c, applications)

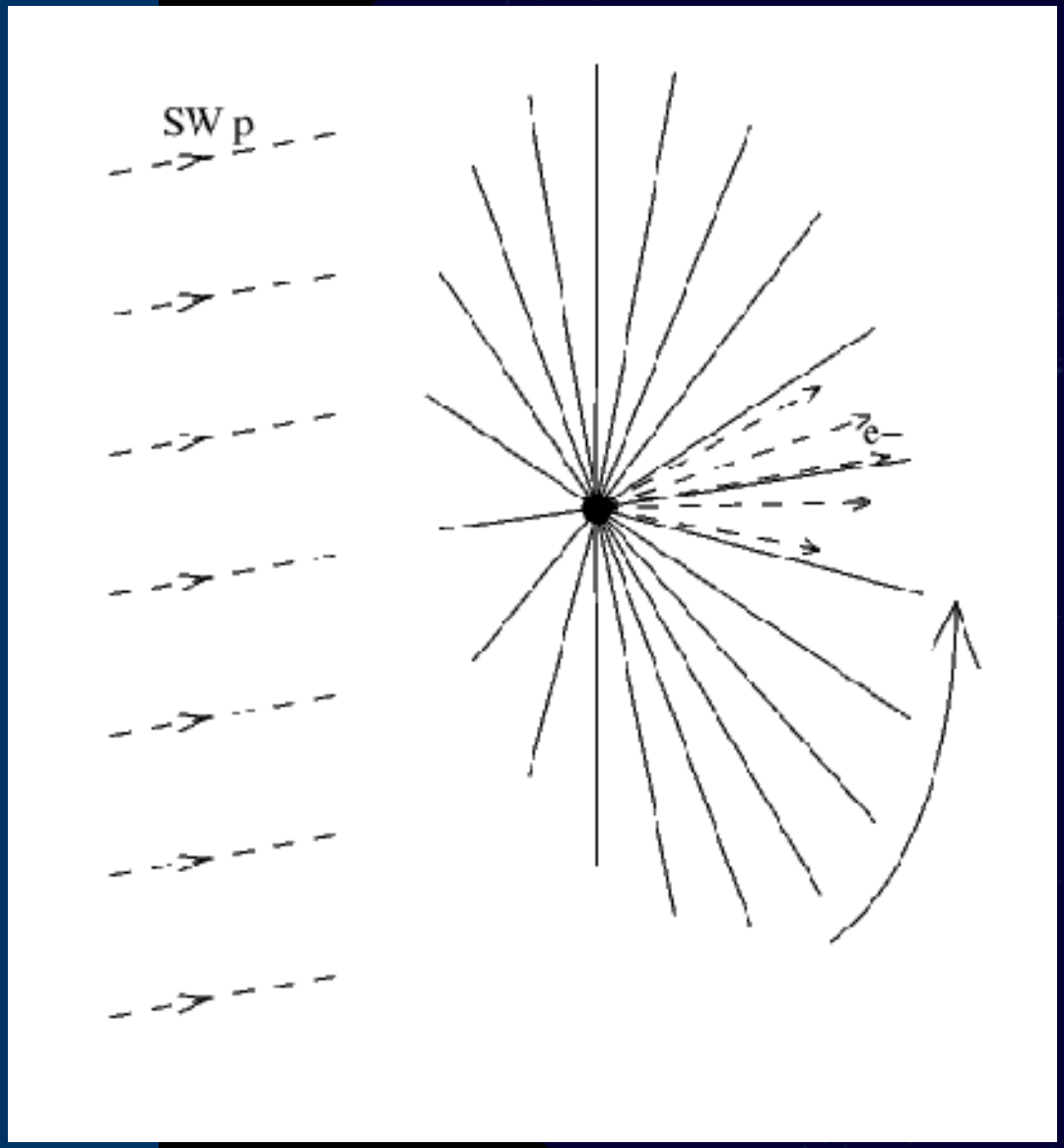
Electric sail working principle

- **Thin and long** positively charged **tethers**, forming obstacle for solar wind protons and transferring momentum from them
- **Electron gun** maintains the positive potential
- Radial, **centrifugal** deployment
- Thrust on each tether depends on its voltage, which is tuned individually by **potentiometers**
  - Helicopter-like algorithm for spinplane turning (attack angle <--> potential)

Main features

- Simple, scalable architecture
  - Set of small, identical reels
  - Longer tethers or more reels ==> larger thrust
- High performance
  - Electric width of wire ~10^6 times physical width (20 m/20 μm)
- Natural way of guiding
  - Thrust vectoring ~ +-30 deg
  - Electric throttling
- Thrust decreases slowly with r
  - E-sail: $F \sim 1/r^{7/6}$
  - Solar sail & ion engine: $F \sim 1/r^2$

Electric sail working principle



Typical parameters

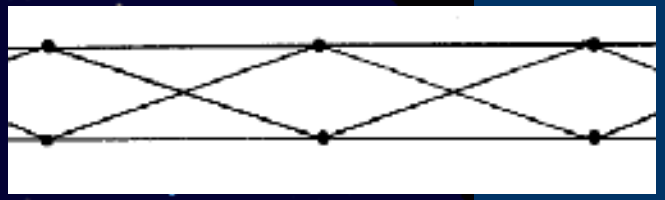
- Solar wind dynamic pressure ρv^2 ~ 2 nPa at 1 AU
- Tether 'electric radius' ~ Debye length λ_{De} ~ 20 m
- N=50-100, L=20 km, r_w=10 μm
- $F \sim \rho v^2 \, NL \, \lambda_{De}$~0.1-0.2 N
- $a = F/m$~1-3 mm/s^2
- Electron current $I = NL \, en(2eV_0/m_e)^{1/2} \, 2 \, r_w$~10-50 mA
- V_0=15-25 kV
- dF/dz~50-100 nN/m

Needed hardware

- Tethers and their reels (50-100)
- Solar-powered electron gun/guns (~500 W)
- Spin initiation: either
  - conventional propulsion unit with arms (jettisoned), or
  - obtain spin from solar wind by 'pumping' procedure, or
  - “Siamese Twins” solution (spacecraft pair)
- Potentiometers & tunable length for tethers
- S/C attitude/spin control thrusters (low power)
- Sensors for guiding+navigation:
  - tether orientation sensors, accelerometer
  - electron detector for measuring s/c potential (optional)
  - tether current measurement (optional)

Tethers and their reels

- Multiple wire because of micrometeoroids
- N=50-100, d=20 μm, n_{mult}=4, L=20 km
- "Hoytether" approach
- Transverse spacing ~2 cm



- Small ballast weight to initiate deployment
- Tensile strength and conductivity
  - Inner solar system: conductivity important
  - Outer solar system: tensile strength more important
- Low deployment speed (some 0.1-1 cm/s)
- Probably need to fine-tune length also during flight

Ways to increase thrust

- RF heating of trapped electron cloud?
  - Hard to model
  - Easy to test in space
  - Could possibly *multiply* thrust (!)
- More tethers (baseline 50-100)
  - No theoretical limit
- Longer tethers (baseline 20 km)
  - At >100 km length, resistance & strength issues

Are there some issues?

- Meteoroid cuts (under control)
  - Tether cut may be fatal if causes tether collision
  - Won't happen if tethers not in same plane
- Getting stuck of damaged tether when retracting?
  - Need to make prototype tether to test this
  - If problem, use monofilament for retractable part (root)
  - Or always reel tethers out only, never in
- Stochastic nature of solar wind
  - Not a problem in practice
  - Thrust varies much less than solar wind
- Oscillations due to CTE if driving into eclipse?
  - Potential problem only in some planetary missions

Scientific mission applications

- Off-Lagrange point solar wind monitor
- Mission visiting multiple asteroids
- Cluster of Kuiper belt/Centaur object flybyers
- Interstellar Heliopause Probe (IHP)
- Other planetary, solar, etc. missions:
  - If payload is small, delta-v can be very impressive
  - If payload is normal, delta-v is SEP-class, but propulsion system is more lightweight
  - If payload is heavier, delta-v is small, but payload ratio is high
  - Electrical throttling ability can be important for some missions

Space validation path

- First test mission
  - High elliptic orbit, or Moon orbit
  - 8 x 1 km tethers
  - 50 kg dry, 200 kg wet (if from LEO)
  - Measure thrust by accelerometer (~10^{-6} m/s²)
  - Test electron heating
  - Double-use tethers as dust detectors (science bonus)
  - Cost: ~5 Meur (if using cheapest parts)
- Second test mission
  - Longer tethers, real propulsive thrust
  - Some scientific target (maybe asteroid)
  - Demonstrate thrust vectoring
  - Cost: ~20-35 Meur

Commercial applications?

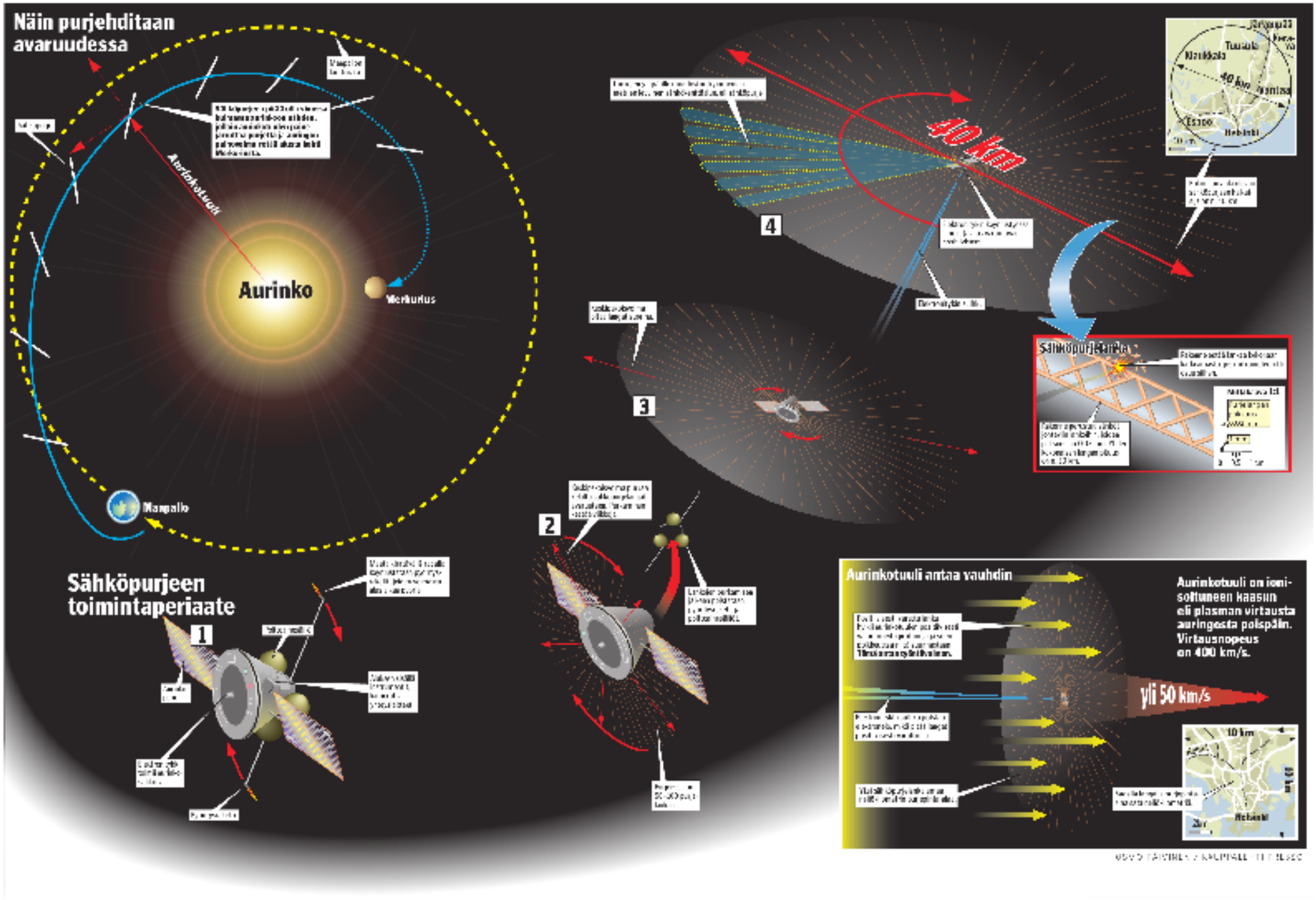
- Off-Lagrange solar wind monitor
- Transfer service for Asteroid Resource Utilisation

Summary

- Solar wind sailing seems possible and practical
- Validation:
  - First space test: measure thrust by accelerometer
  - Second test: E-sail propelled demo mission
- Numerous applications:
  - IHP
  - Off-Lagrange space weather monitor
  - Other Solar System missions (solar, asteroid, Kuiper)
  - Logistics chain for asteroid resource usage

Artistic pictures published in popular-scientific magazines:

- Kauppalehti Presso (Finnish Business Daily), Jan 27, 2007
- Allt om vetenskap (All about science), number 4/2008 (10-page cover story)
- Air and Cosmos (French journal), May 30, 2008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Aurinko
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40 km
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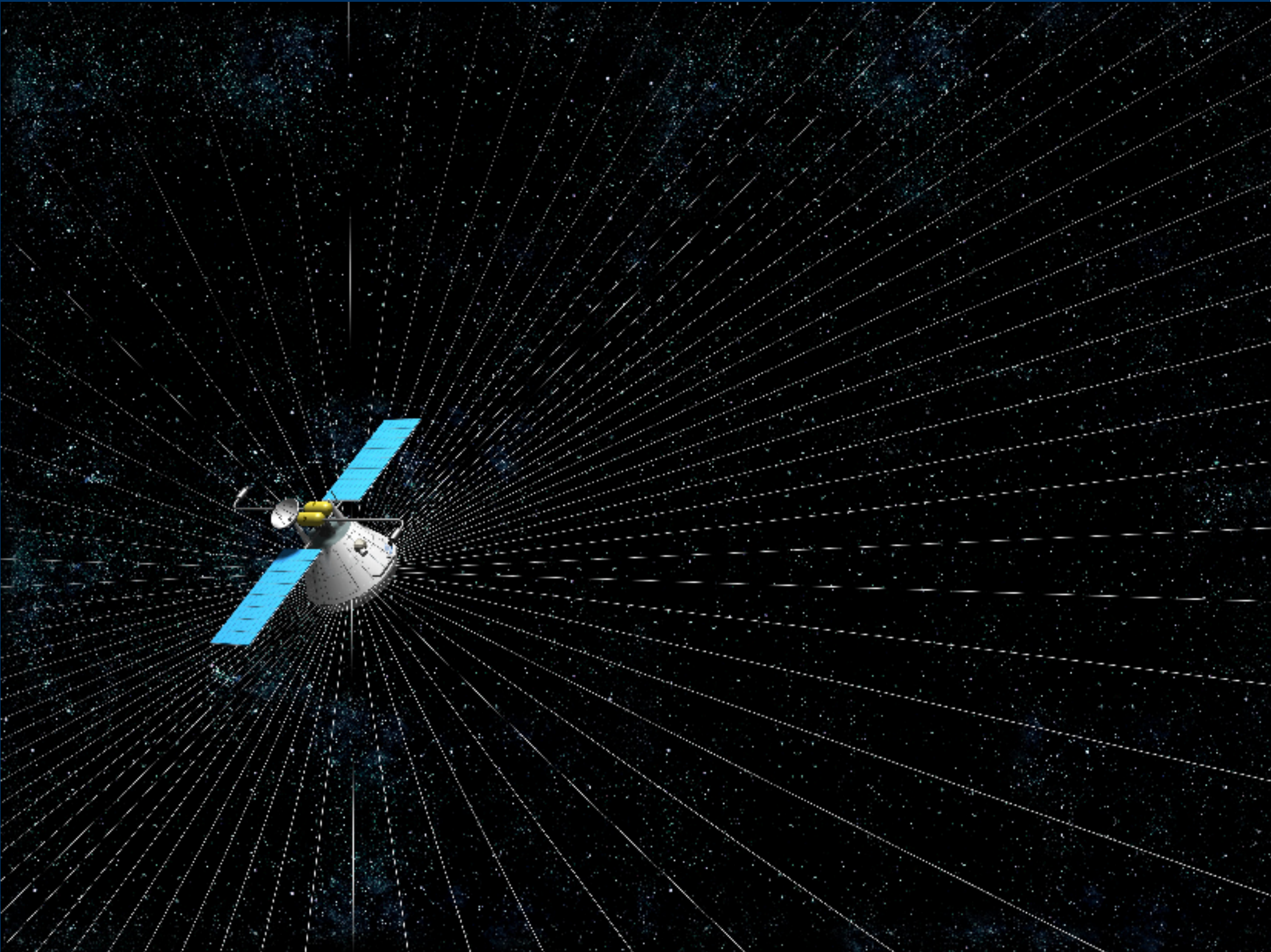
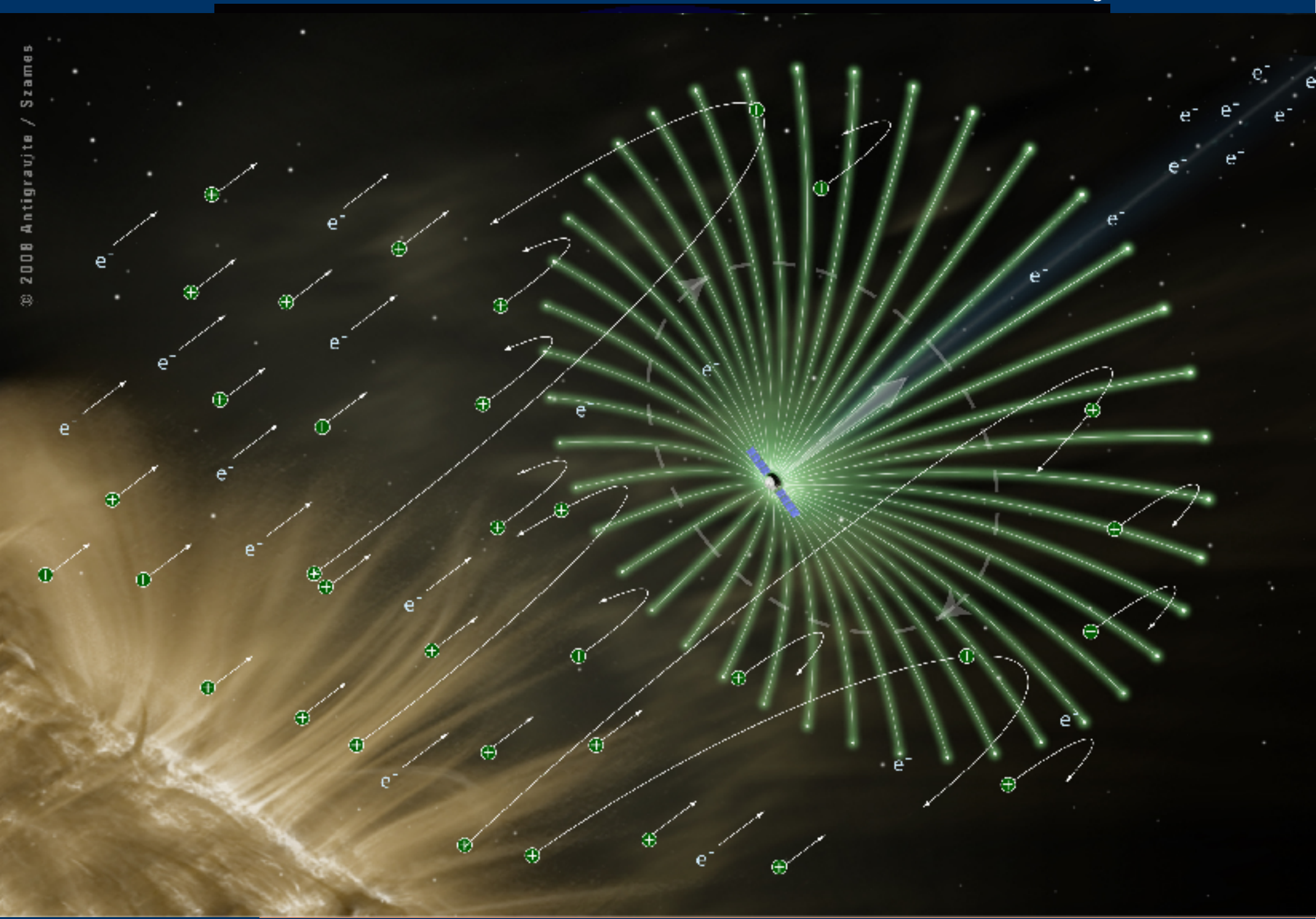
yli 50 km/s
10 km

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