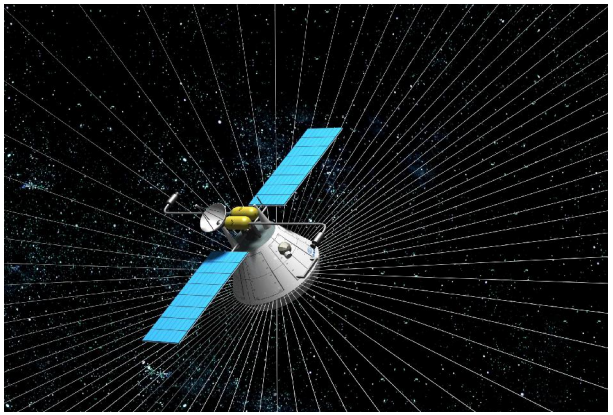
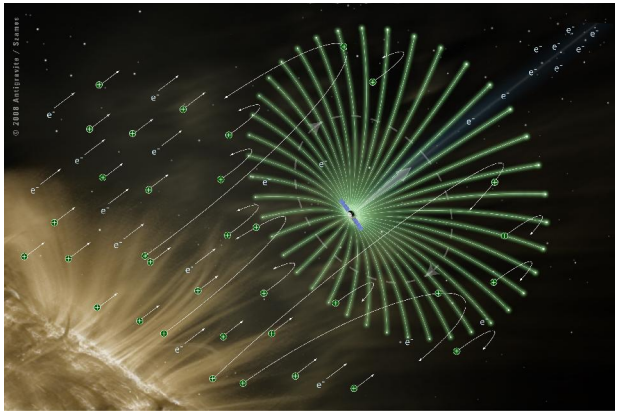
ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE





Physics of thrust prediction of Solar Wind Electric Sail propulsion system

Pekka Janhunen

Finnish Meteorological Institute, Helsinki

(Kumpula Space Centre)

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Collaborators (partial list)

Petri Toivanen, Risto Kurppa, Juha-Pekka Luntama, Arto Sandroos, Jouni Polkko, Walter Schmidt, Markku Mäkelä, Ari-Matti Harri (FMI), prof. Edward Haeggström, Henri Seppänen, Sergiy Kiprich, Jukka Ukkola (Univ. Helsinki), Jouni Envall, Mart Noorma, Silver Lätt (Univ. Tarto), prof. Simo-Pekka Hannula, Yossi Ezer, Eero Haimi, Tomi Suhonen (TKK/MAT), prof. Aarne Halme, Tomi Ylikorpi (TKK/AUT), Pasi Tarvainen, Erkki Heikkola, Antti Niemistö (Numerola Oy), prof. Mikhail Zavyalov, prof. Slava Linkin, Pavel Tuyruykanov (IKI, Moscow), prof. Giovanni Mengali, Alessandro Quarta (Univ. Pisa), Lutz Richter, Olaf Krömer (DLR-Bremen), Greger Thornell, Henrik Kratz (ÅSTC, Uppsala).

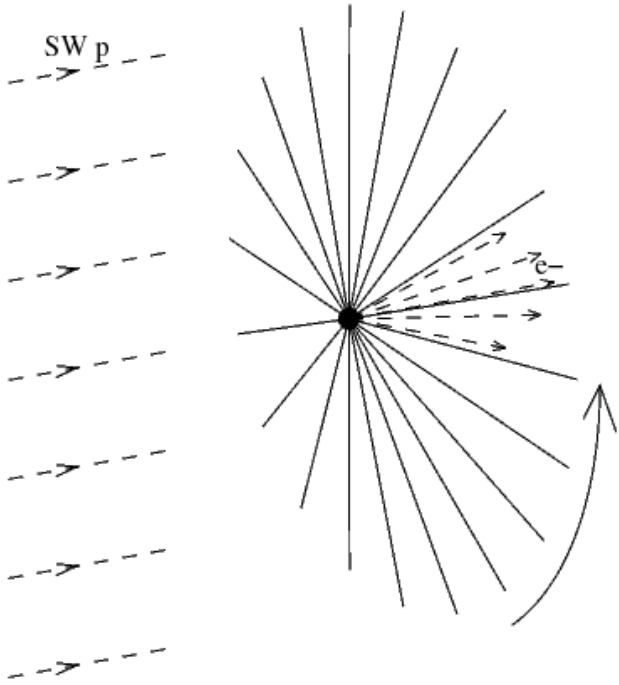
Acknowledgements: Mikhail Uspensky, Harri Haukka, et al. (FMI), Svenja Stellmann (now Bremen), Rami Vainio (Univ.Helsinki), Robert Hoyt (Tethers Unlimited Inc.), Giovanni Vulpetti (Rome), prof. Giancarlo Genta (Polytech.Torino), prof. Pierre Rochus, Yvan Stockman (Univ.Liege), Fredrik Bruhn (ÅAC, Uppsala), prof. Viktor Trakhtengerts(*), Andrei Demekhov (Nizhny Novgorod)

Outline

1. Electric Solar Wind Sail: what is it
2. PIC simulation results: trapped electrons included
3. 3-D removal mechanism for trapped electrons
4. “Electrosphere” principle for estimating thrust
5. Five times higher thrust?

Electric Solar Wind Sail

- Use solar wind for spacecraft propulsion
- Coulomb interaction between solar wind and long, thin, positively charged tethers (10-20 km, 25-50 um wire, +20-40 kV)
- Centrifugal stretching, Potentiometer guiding & navigation
- High-performance, relatively simple, general-use propellantless propulsion technique
- First idea Janhunen 2004
- In its present form Janhunen 2006



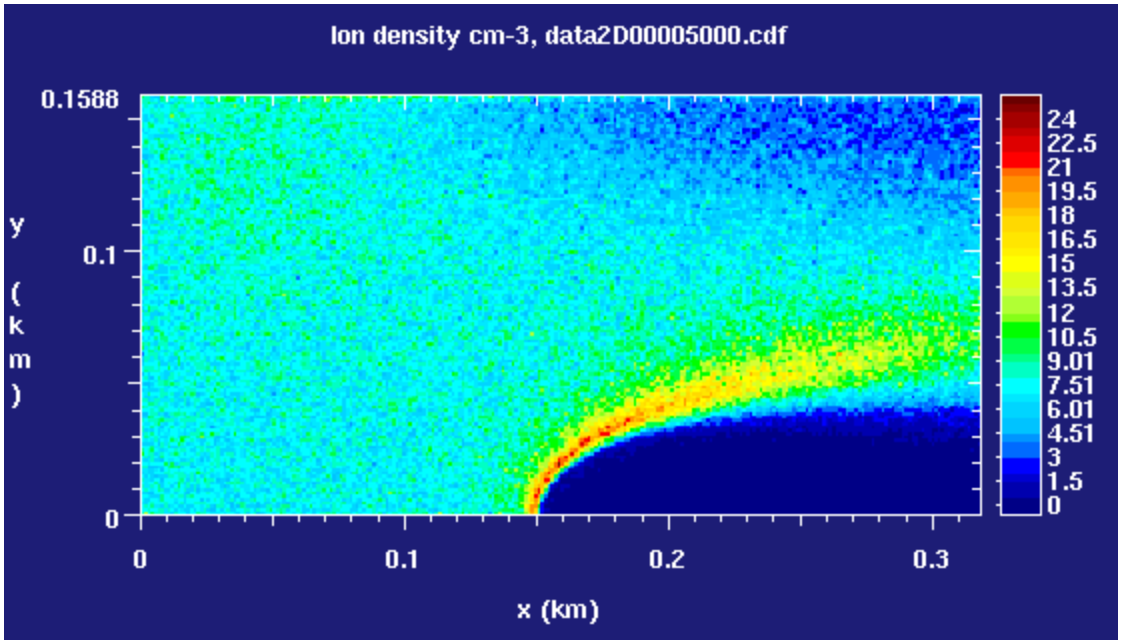
Elementary process of Electric Sail

- Solar wind protons repelled by charged tether
- Proton pile-up on “dayside”, proton depletion on “nightside”
- Resulting electric field pushes charged tether outward from Sun
- (Thrust vectoring up to ~30^{o} possible, since force always perpendicular to tether)
- *Task:* Predict electron sheath size and thrust per unit length on positively charged wire in flowing solar wind plasma

PIC simulation of electric sail

- (Janhunen and Sandroos, 2007)
- Direct, time-dependent electrostatic particle simulation
- Includes potential ramp-up phase which creates population of trapped electrons
- Number of trapped electrons is independent of the speed at which the potential is ramped up
- Trapped electrons produce extra shielding which decreases E-sail thrust
- In purely 2-D case there is no apparent mechanism that could remove trapped electrons (except very slow, collisional ones)

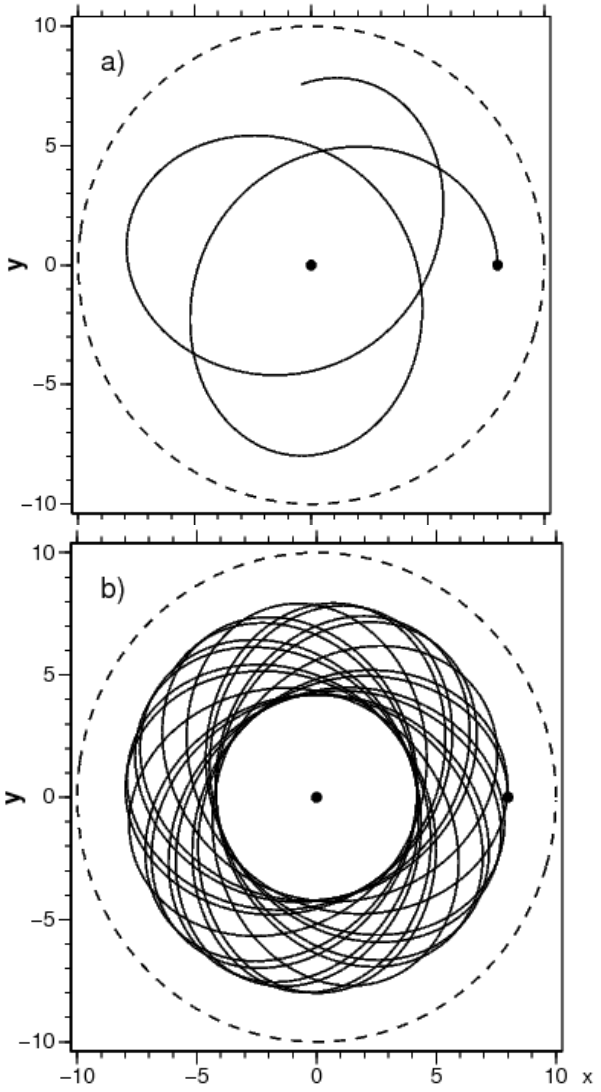
PIC simulation of electric sail



- Challenges:
  - High e V0/Te ratio (V0 ~ 20 kV, Te ~ 10 eV)
  - Logarithmic potential ==> multiscale

Removal mechanism for trapped electrons

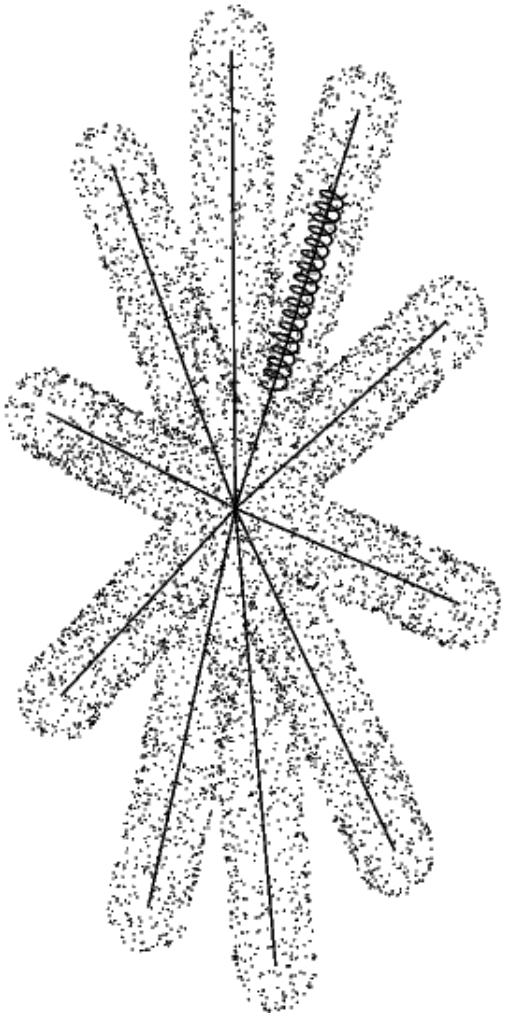
- 2-D electron motion
  - 3 conserved quantities: angular momentum (cyl. symm.), parallel momentum (transl. symm.), energy (static)
- 3-D electron motion
  - 1 conserved quantity: energy (static)
- Electron spirals along tether, is reflected from the tip
- Periodically visits vicinity of spacecraft
- At spacecraft, angular momentum and parallel momentum randomised



Removal mechanism for trapped electrons

- Finite probability that angular momentum becomes very small so that electron has change to hit tether wire and be lost
- Process is rare, but electrons are fast ==> lifetime order of minutes only
- This mechanism removes trapped electrons from vicinity of electric sail tethers

  ==> earlier PIC simulations underestimated the thrust!



“Electrosphere” principle

- Sheath around tether is empty of ions
- Assume it has some constant electron density (can be zero, as zeroth approximation)
- Force balance $(1/2)\varepsilon_0 E^2 = P_{dyn}$ determines “electrosphere” size (assume zero n_e for simplicity) and thrust per length:

$$\frac{dF}{dz} \approx \frac{2.2}{\log(R/r_w)} (V_0 - V_1) \sqrt{\epsilon_0 P_{\mathrm{dyn}}}$$

V0=20 kV, V1=1 kV, Pdyn=2 nPa, R=100 m, rw=1 mm :
dF/dz = 500 nN/m, > 5 times higher than from PIC

What could 500 nN/m E-sail do?

- For example, 100 tethers, 20 km each:
  1 N thrust, scales as 1/r
- Propulsion system mass 100 kg: specific acceleration 10 mm/s^2 (would overcome solar gravity 6 mm/s^2 at 1 AU, 25 km/s delta-v per month)
- Impulse over 10 year lifetime corresponds to 100-ton chemical rocket
- 1000 times more efficient than chemical rocket, 100 times more efficient than contemporary ion engine ...
- Non-Keplerian orbit missions, off-Lagrange space weather monitoring, sample return from Mercury, mission out of heliosphere, easy access to asteroids ...

What should be done next?

- Use static Vlasov-Poisson simulation methods developed by Choiniere, Gilchrist and others, to estimate thrust more quantitatively under assumption of no trapped electrons(?)
- Measure E-sail thrust in orbit (Estonian ESTCube-1 nanosatellite project, planned launch 2012: LEO orbit, 10 m tether)
- Laboratory measurement?

Summary

- Natural mechanism for trapped electron removal was identified in electric sail
- Semianalytic “electrosphere” concept was introduced for thrust estimation, in analogy with magnetosphere
- As a result, electric sail thrust estimates have gone up significantly, to ~500 nN/m, ~1 N total
- The new thrust versus mass estimates are overwhelmingly large for transportation in the solar system