ATOMEXPO-2019

Plasma Thrusters for Space Transport

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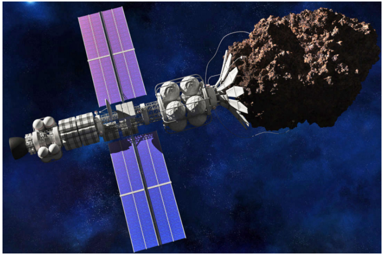
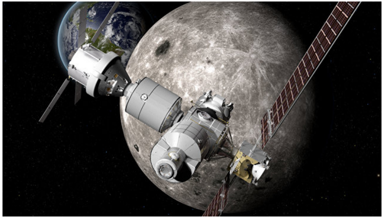
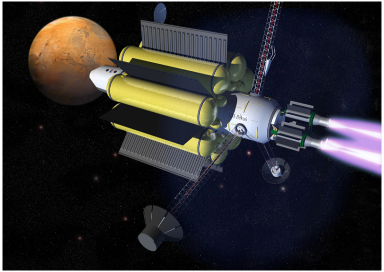
Things to do in space

- Satellite servicing and orbit cleaning
- Base on the Moon
- Manned missions to Mars and other planets
- Asteroid capture and mining, etc.

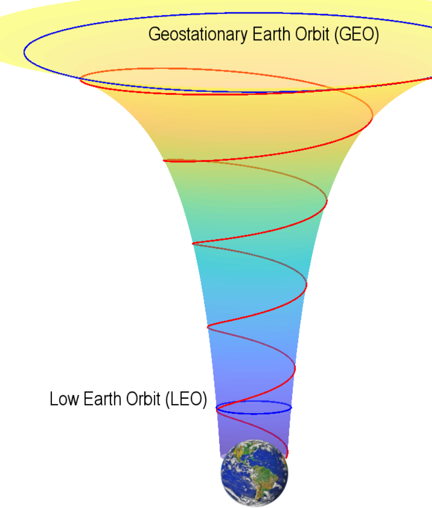






Why are these projects still on paper?

We live at the bottom of gravitational well



Lifting loads in space is expensive

- Payload to LEO: >3000$/kg
- Payload to GEO: >12000$/kg
- Fuel for interplanetary missions has to be lifted too...
- Asteroid mining is not cost-effective

Radiation above LEO is severe

- Low orbital satellites and the ISS are partially shielded by the Earth magnetosphere;
- Manned missions above LEO cannot last too long, less than 1-3 months, due to radiation.

What is needed for space flights

Jet engine

The engine thrust is

$$F = \dot{m}U$$

where $\dot{m}$ is the propellant use rate (kg/s), and U is the exhaust velocity.

Power source

We need power to accelerate the propellant: $W \geq \dot{m}U^2/2$, so that

$$U \leq \sqrt{2W/\dot{m}} \quad \textit{and} \quad F \leq 2W/U$$

Jet propellant

Tsiolkovski formula for the attainable spacecraft velocity:

$$V = U \times ln \frac{m_p + M}{M}$$

where M is the spacecraft mass and m_p is the needed mass of propellant.

Properties of chemical fuels

+ Very convenient two-in-one: power source and propellant;
– Low exhaust velocity: $U < 4.5$ km/s.

Electrojet propulsion

Electromagnetic acceleration of propellant

+ Exhaust velocity can be high and variable, $U \sim 10 - 100$ km/s;
- Needs electrical power source
  - Nuclear
  - Solar
- Very low thrust at moderate power levels ($F < 1N/10kW$)
- There are power losses for ionisation
- Best propellant (Xe) is rare and expensive

Power sources

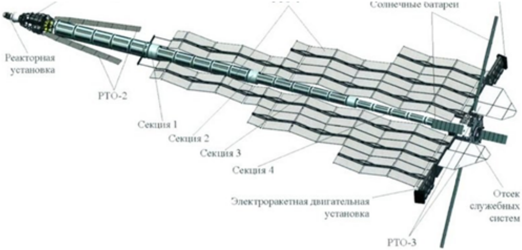
Nuclear

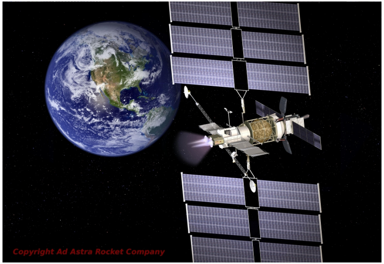
+ Nuclear energy content is high;
– Reactors are heavy;
– Conversion to electricity requires cooling panels;
– Need radiation shielding.

Solar

+ Clean, cheap, renewable;
– Area of solar panels ($\lesssim 1kW/m^2$).

Solar power is optimal for small spacecraft, manned missions to planets need nuclear power sources.





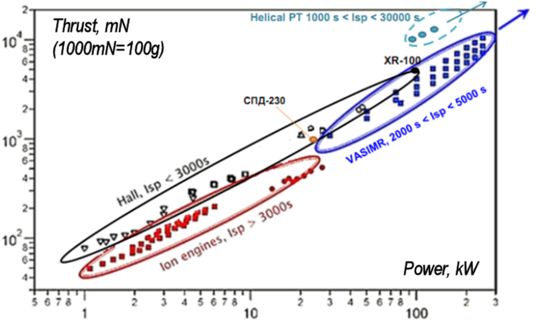
Engine thrust and propellants

Exhaust velocity

- Low engine thrust increases travel time;
- High exhaust velocity reduces thrust, optimum is at $U \sim 30 - 50\ km/s$;

Thrust: $F = 2(W - W_{loss})/U$

- $W_{loss} = \dot{m}I/\mu$, where I is energy loss per atom, and μ is the atomic mass;
- Heavy and chemically inactive gas (Xenon) is the optimal propellant;
- Using lighter propellants requires lower I (partial ionization).



- Existing electrojet engines ($W < 200kW$) generate thrust only up to 10N=1kg;
- Manned interplanetary missions need $W > 10MW$.

Main electrojet types

Electrothermal

- Arc discharge or RF heating

Electrostatic

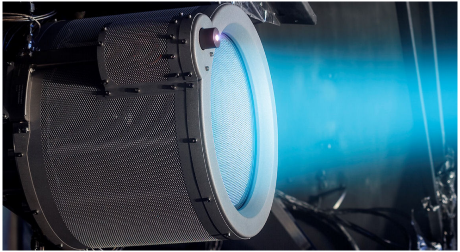
- Gridded ion thrusters
- Hall effect thrusters (SPT and TAL)

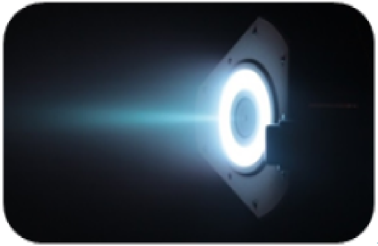
Electromagnetic

Acceleration can be based on:

- Heating + magnetic nozzle effect (VASIMR, Helicon, etc.)
- Ampere force (MPD, КСПУ, etc.)
- RF ponderomotive force...

Ion thruster





Hall (SPT)

Hall plasma thrusters

SPT (by OKB “Fakel”)

- More than 250 launched;
- Orientation and orbital support of satellites and small spacecraft;
- Five types, up to 25kW/1N.

Rocketdyne XR-100 (100kW)

- The largest SPT (in development).

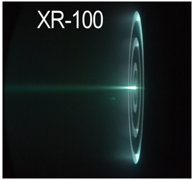
TAL

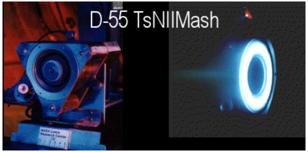
- Should be capable of higher power and lifetime;
- Cannot exceed SPT yet.

SPT-140

FAKEL

Development level	QM
Power	3000 / 4500 W
Discharge voltage	300 V
Thrust	193 / 290 mN
Specific impulse	1680 / 1770 s
Efficiency	50 / 55%
Lifetime	>9000 h
Mass	8.4 kg
Dimensions	317×270×109 mm





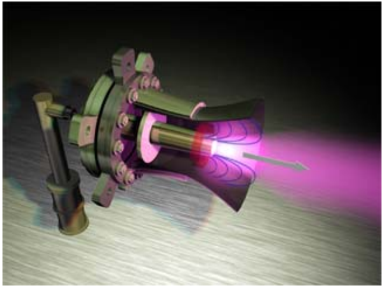
Coaxial plasma engines

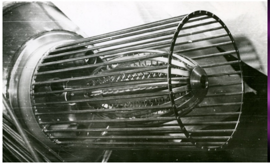
MPD-type thrusters

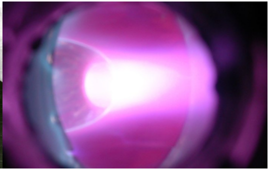
- High-power discharge, pulsed or continuous;
- Very high erosion / low lifetime.

Coaxial high-current plasma thruster (КСПУ)

- Very high power (up to 10MW) / designed for higher lifetime;
- Experimental devices in Troitsk and Kharkov are used as plasma-jet sources;
- No 10MW power sources in space...





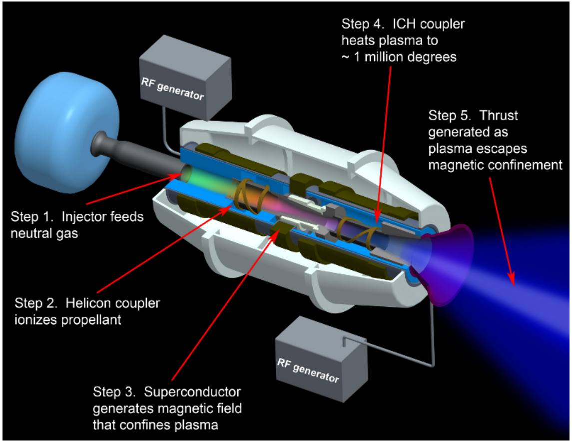


VASIMR plasma engine by Ad Astra Co, USA

In development:

- High-power (100kW up to 10MW);
- Variable exhaust velocity;
- Can work with argon;
- Electrode-less design: durable, with low erosion rates;
- Requires hi-tech superconducting magnets and RF generators.

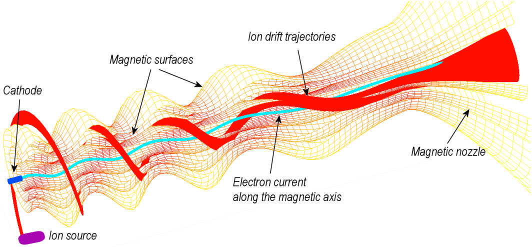
Development stage is close to test flights of 100kW version in space.

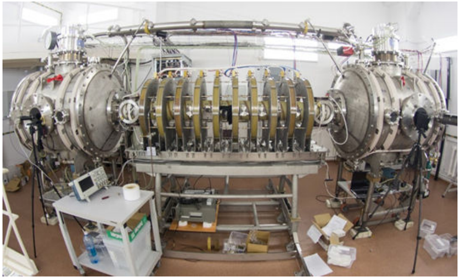


Helical plasma thruster (BINP, Novosibirsk)

In development with OKB "Fakel":

- MW-class/variable exhaust velocity, similar to VASIMR;
- New, screw-pump-like plasma acceleration mechanism;
- Can (potentially) work with diverse propellants at low ionization (such as pulverized asteroids);
- Early research stage of development, working principle is experimentally tested in SMOLA device.





Conclusion

New nuclear and plasma technologies for space transport are in development. They can open up a new era of exploration and resource extraction in space.