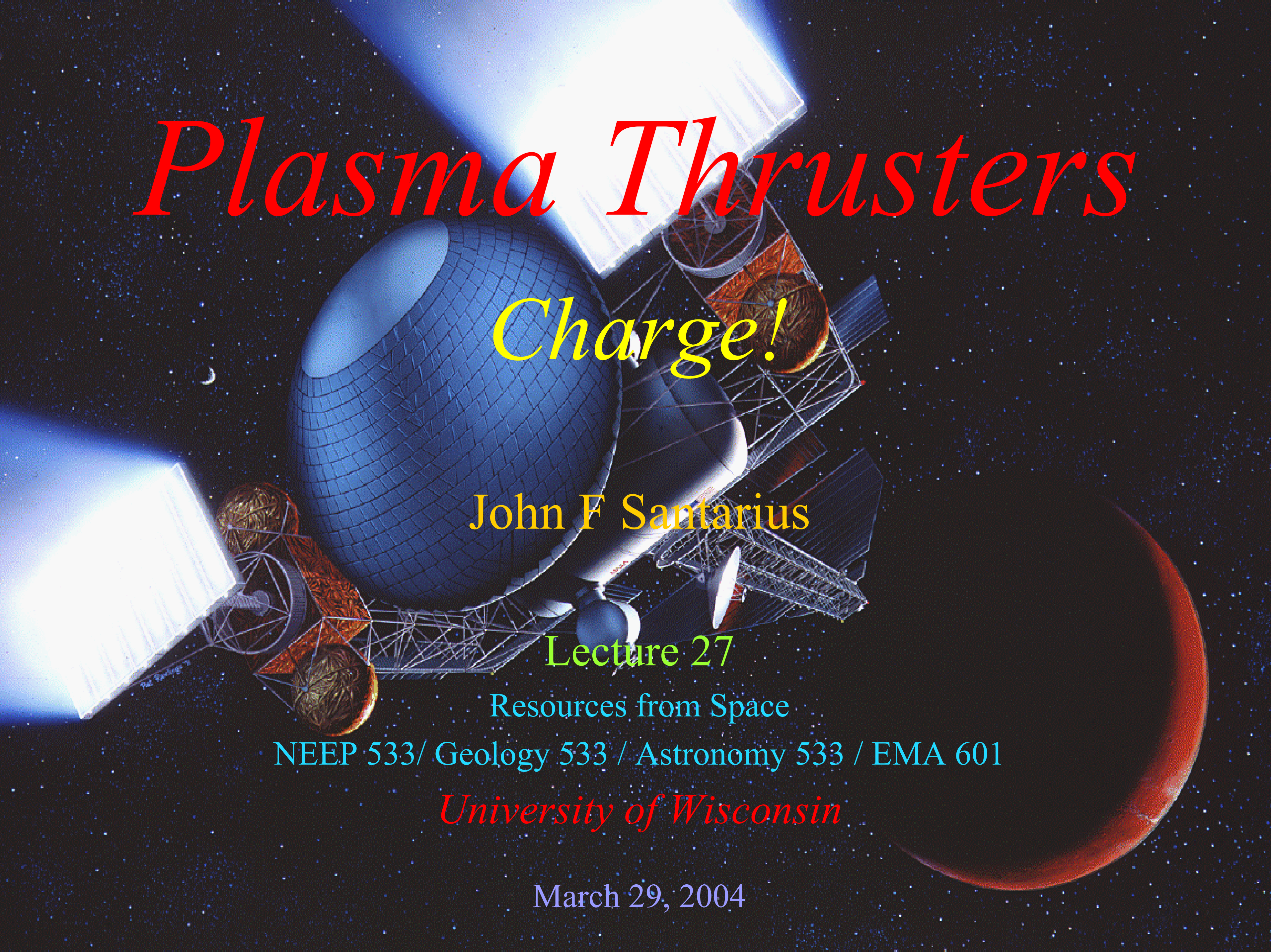

Plasma Thrusters

Charge!

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Lecture 27

Resources from Space

NEEP 533/ Geology 533 / Astronomy 533 / EMA 601

University of Wisconsin

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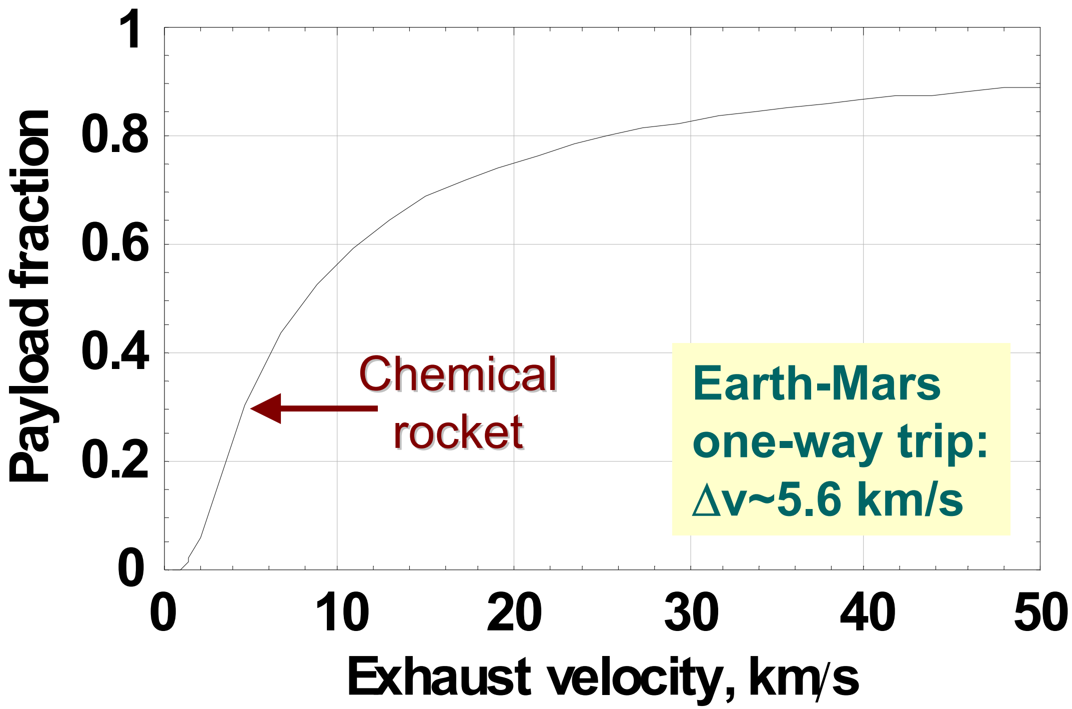
Key Points

- Low-thrust rockets:
  - Provide good efficiency for high-energy missions and
  - Give flexible options for mission trajectories.
- Several useful plasma-thruster options exist, with a wide range of exhaust velocity capabilities.

Why Do We Care about Plasma Thrusters? High Exhaust Velocity Gives Large Payloads

- This plot of the rocket equation shows why high exhaust velocity historically drives rocket design: payload fractions depend strongly upon the exhaust velocity.

$$\frac{M_f}{M_i} = \exp\left(\frac{-\Delta v}{v_{ex}}\right)$$

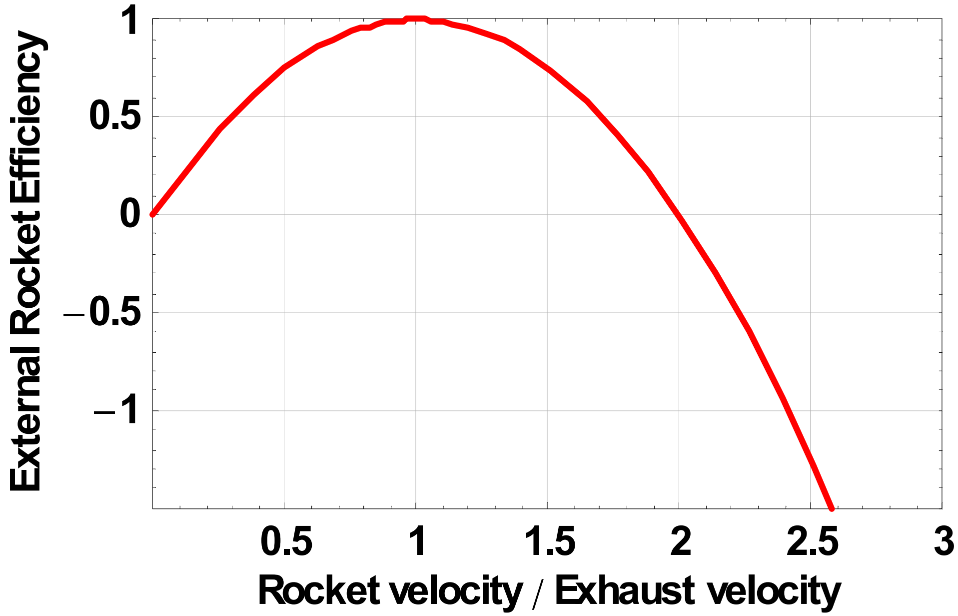


Plasma Propulsion Has a Long History

Year	*People*	*Event*
1906	Robert H. Goddard	Brief notebook entry on possibility of electric propulsion
1929	Hermann Oberth	*Wege zur Raumschiffahrt* chapter devoted to electric propulsion
1950	Forbes and Lawden	First papers on low-thrust trajectories
1952	Lyman Spitzer, Jr	Important ion-engine plasma physics papers
1954	Ernst Stuhlinger	Important analysis. Introduces *specific power*.
1958	Rocketdyne Corp.	First ion-engine model operates on Earth
1960	NASA Lewis (Glenn) & JPL	Establish NASA's electric propulsion research program
1964	USSR	Operates first plasma thruster in space (Zond-2)
1998	US	Deep Space 1 electrostatic ion thruster used in space

Defining Rocket Efficiency Can Be Tricky

- For example: *External Rocket Efficiency*
  ≡ increment in rocket kinetic energy divided by kinetic energy change generated by rocket engine.



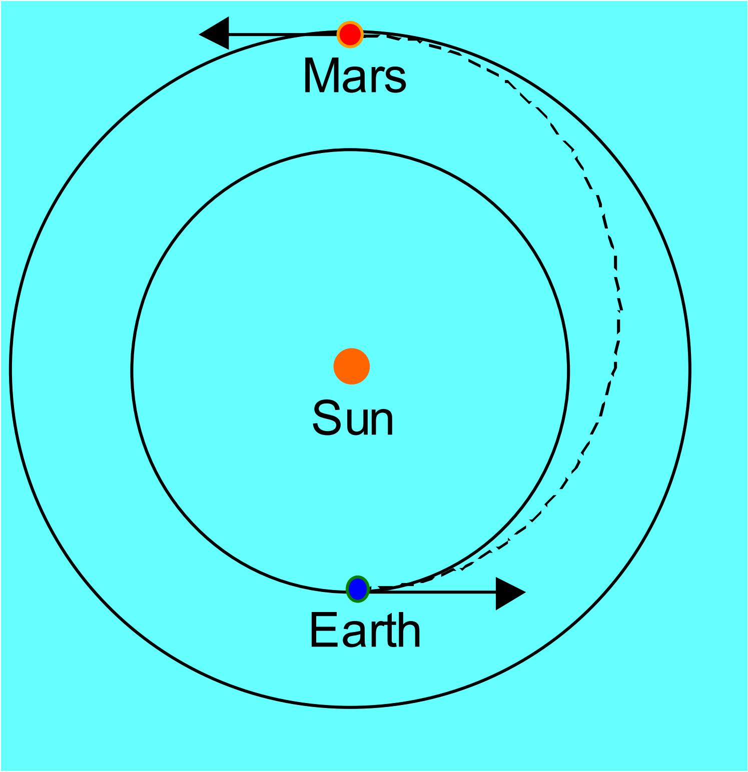
- ***Negative efficiency!*** Exhausted propellant carries more kinetic energy than it had as part of the rocket.

How Do Separately Powered Systems Differ from Chemical Rockets?

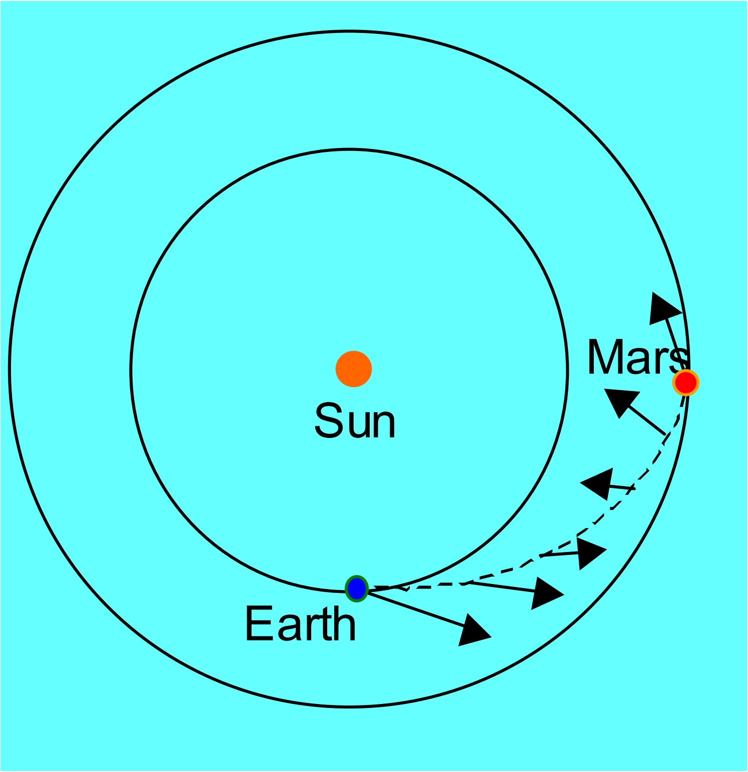
- Propellant not the power source.
- High exhaust velocity ($\gtrsim 10^5$ m/s).
- Low thrust ($\lesssim 10^{-2}$ m/s$\} \equiv 10^{-3}$ Earth gravity) in most cases.
- Thrusters typically operate for a large fraction of the mission duration.
- High-exhaust-velocity trajectories *differ fundamentally* from chemical-rocket trajectories.

Taking Full Advantage of High Exhaust Velocity Requires Optimizing Trajectories

Chemical rocket trajectory
(minimum energy)



Fusion rocket trajectory
(variable acceleration)

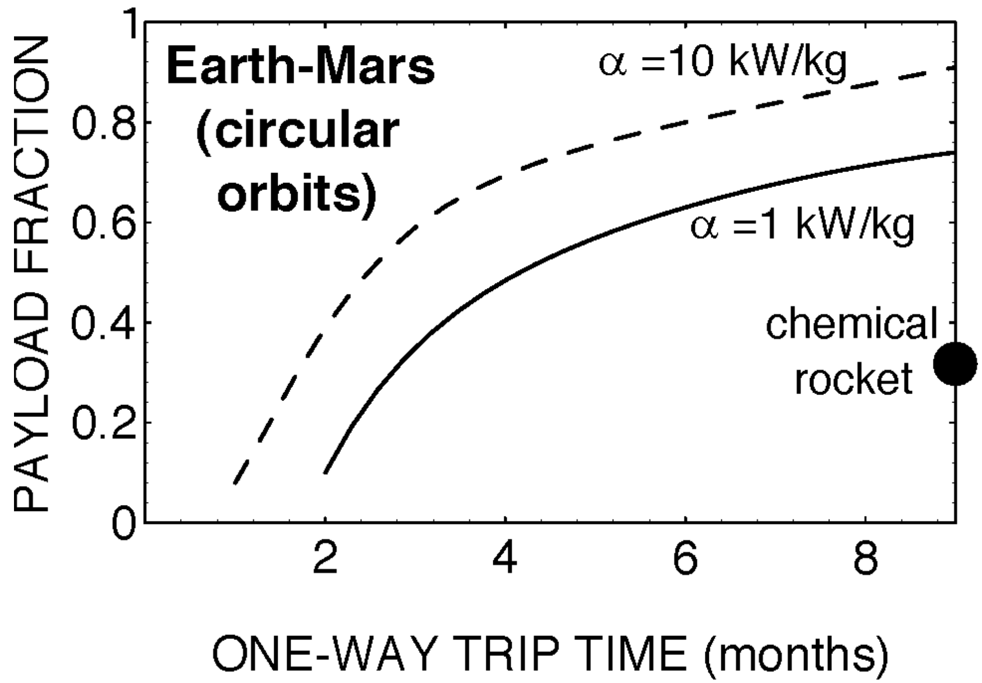


Note: Trajectories are schematic, not calculated.

Efficient Solar-System Travel Requires High-Exhaust-Velocity Propulsion

- Electric power can be used to drive high-exhaust-velocity plasma or ion thrusters, or fusion plasmas can be directly exhausted.
- Allows fast trip times or large payload fractions for long-range missions.
- Uses relatively small amounts of propellant, reducing total mass.

Fusion rocket



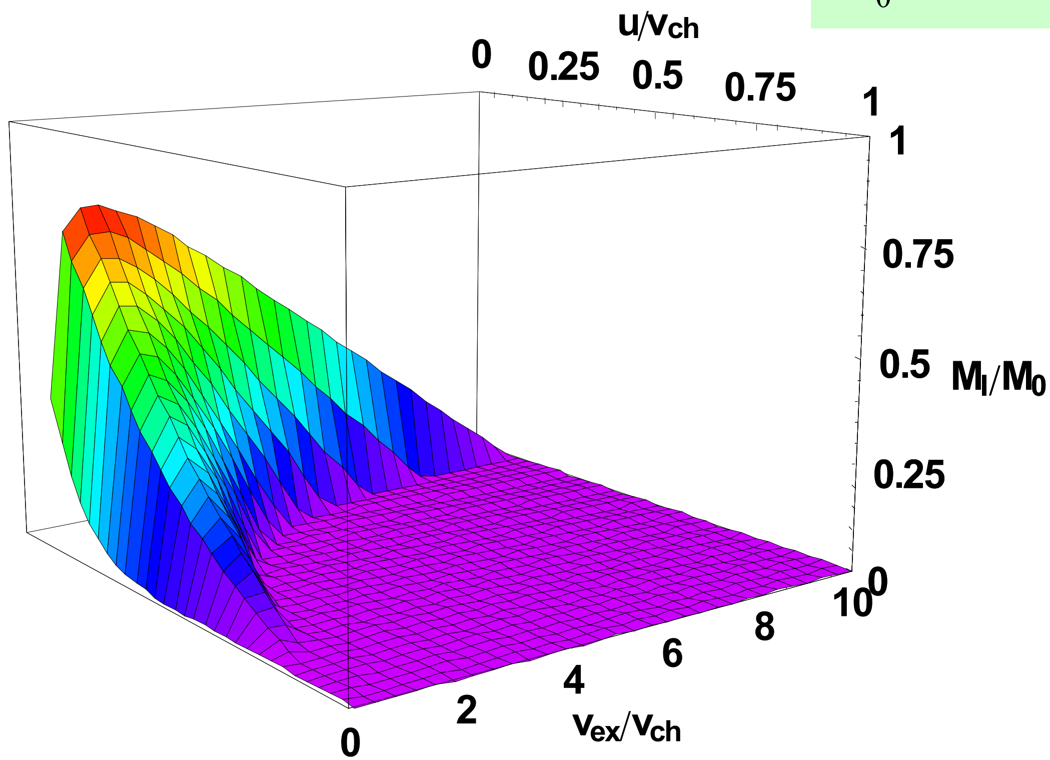
α [kW/kg] ≡ specific power = P_w / M_w

Rocket Equation for Separately Powered Systems

- Explicitly including the power-plant mass modifies the rocket equation:

$$\frac{M_l + M_w}{M_l + M_w + M_p} = \exp\left(\frac{-\Delta v}{v_{ex}}\right) \Rightarrow$$

$$\frac{M_l}{M_0} = \exp\left(\frac{-u}{v_{ex}}\right) - \frac{v_{ex}^2}{v_{ch}^2}\left[1 - \exp\left(\frac{-u}{v_{ex}}\right)\right]$$



M_p = propellant mass

M_l = payload+structure mass

M_w = power and propulsion system mass

$u \equiv$ mission velocity increment

$v_{ch} \equiv (2\alpha\tau)^{½}$ = characteristic velocity

$v_{ex} \equiv$ exhaust velocity

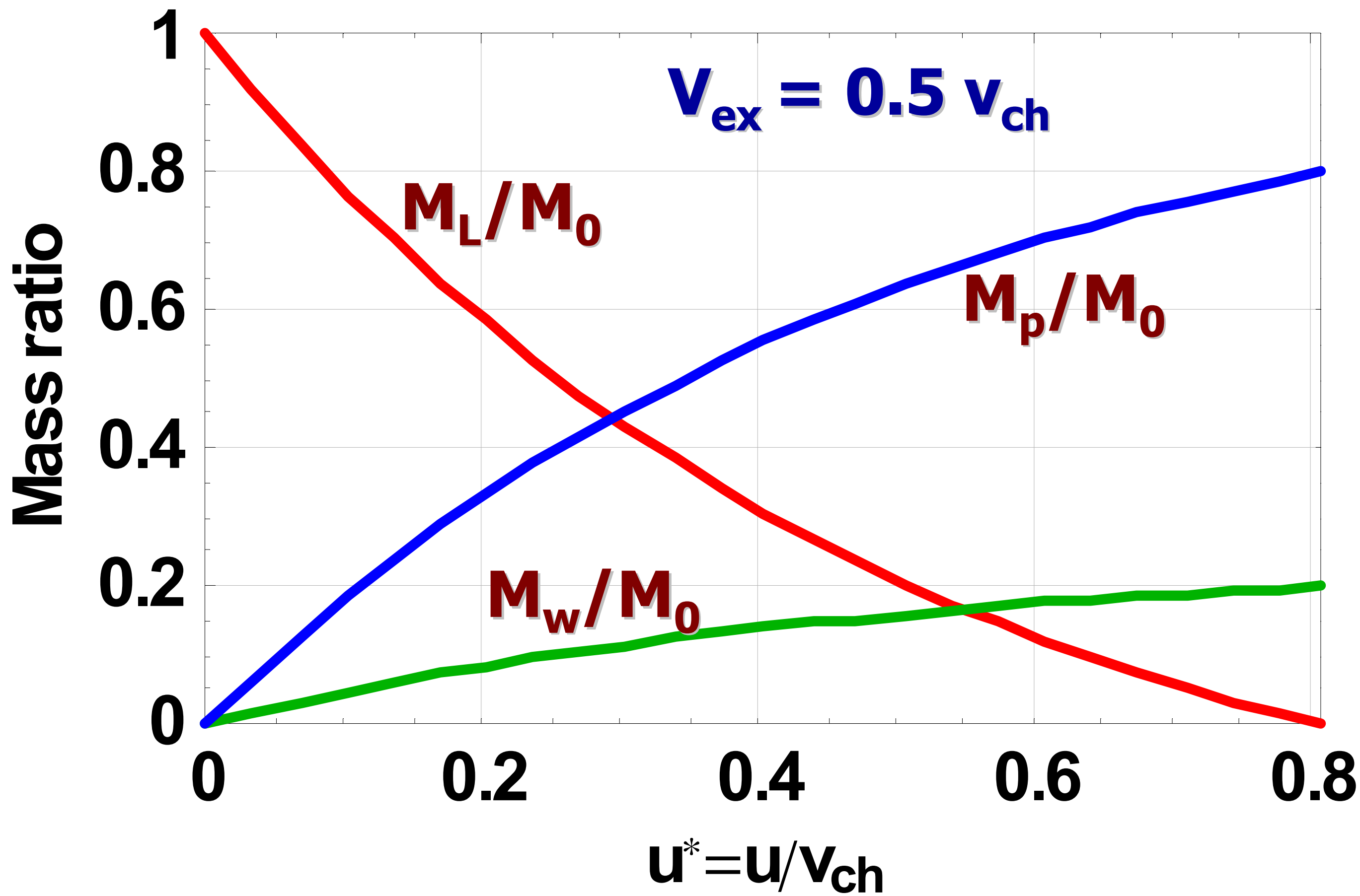
Mass Ratios Vary Simply with u/v_{ch} and v_{ex}/v_{ch}

$M_w \equiv$ power plant mass

$M_L \equiv$ payload mass

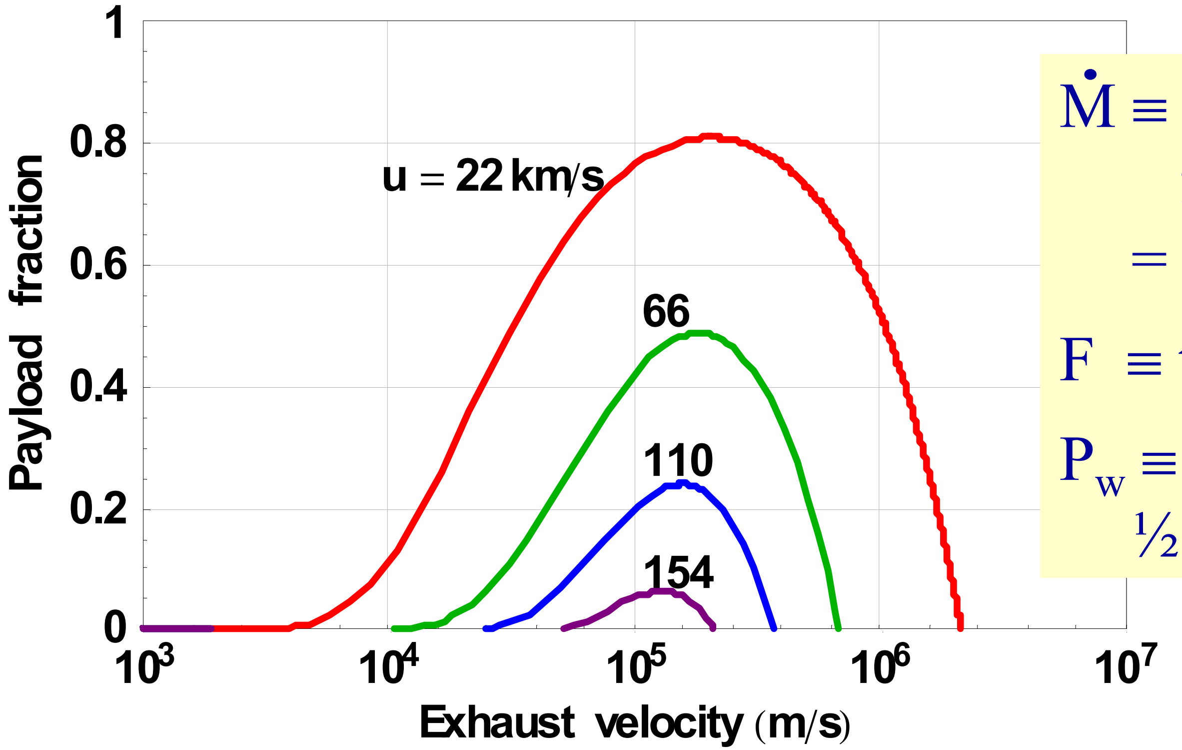
$M_p \equiv$ propellant mass

$M_0 \equiv$ total mass



Earth-Mars Mission Characteristic Velocity Example: α=1 kW/kg; τ=9 months (one-way)

- Characteristic velocity $\equiv v_{ch} \equiv (2\alpha\tau)^{1/2} = (2\times1000\times\frac{3}{4}\times3.15\times10^7)^{1/2}$ m/s = 220 km/s
  - Note: remember to use *W/kg not kW/kg* for α when calculating v_{ch}!
- $v_{ch} \approx$ 40 times Hohmann Δv (5.6 km/s for Earth-Mars missions)



$\dot{M} \equiv$ propellant flow rate $= M_p/\tau$

$F \equiv$ thrust $= \dot{M} v_{ex}$

$P_w \equiv$ thrust power $= \frac{1}{2} \dot{M} v_{ex}^2$

Earth-Mars Mission Example
Summary Parameters

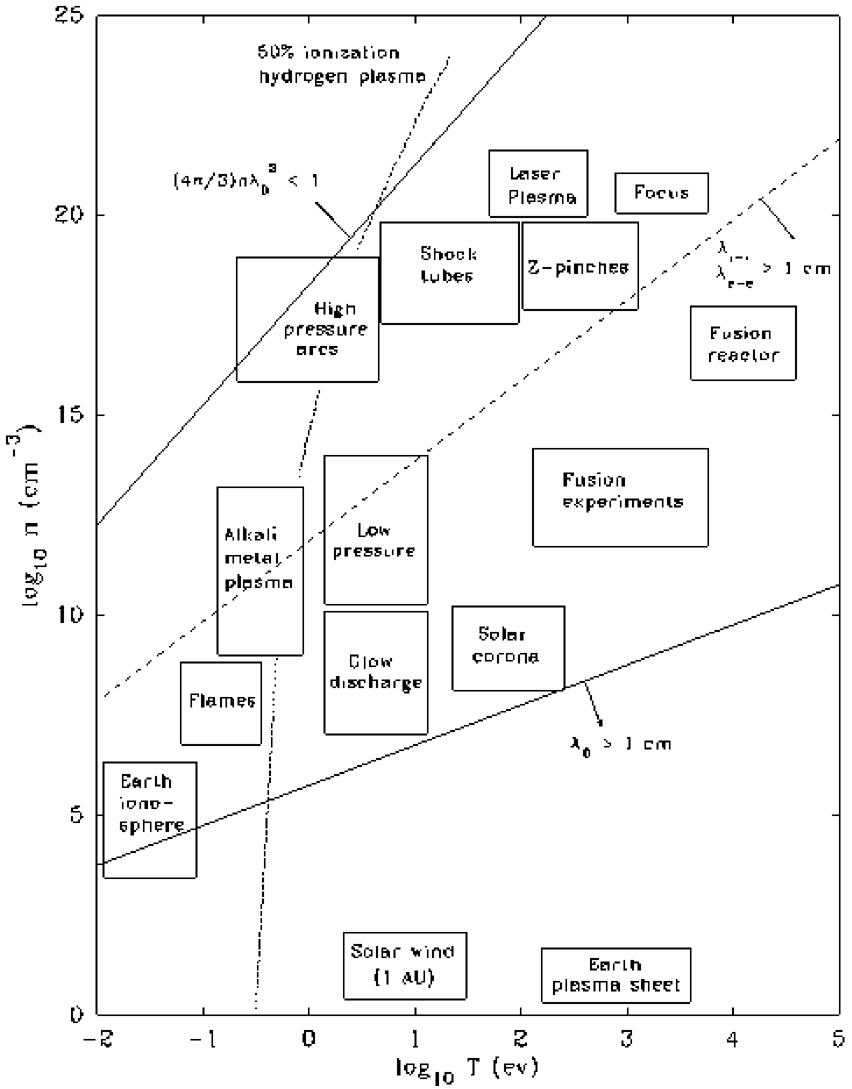
Parameter	*Low-Thrust*	*Chemical*
One-way travel time	258 days	258 days
Specific power	1 kW/kg	∞
Characteristic velocity	150 km/s	--
Exhaust velocity	119 km/s	4.5 km/s
Total velocity increment	24 km/s	5.6 km/s
Distance traveled	5.5 AU	5.5 AU
Propellant flow rate	~1.5 g/s	?
Thrust force	0.17 kN	?
Initial thrust-to-weight	0.00012	?
Payload ratio	0.7	0.29

Earth-Mars Mission Example
Summary of Masses

	Low-Thrust	*Chemical*
Payload	100 Mg†	100 Mg†
Power and propulsion	10 Mg	0 Mg
Propellant (acceleration phase)	17 Mg	--
Propellant (deceleration phase)	16 Mg	--
Propellant total	33 Mg	244 Mg
Total initial mass	143 Mg	344 Mg

† Note: 1 Mg ≡ 1 tonne

Plasmas (Hot, Ionized Gases) Exist in Many Different Regimes



Governing Principles for Analyzing Plasma Thrusters

- Maxwell's equations

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

- Force equation

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} - \nabla P$$

- Atomic physics
- Plasma-surface interactions
- Sheath physics
- Statistical mechanics
- Magnetohydrodynamics

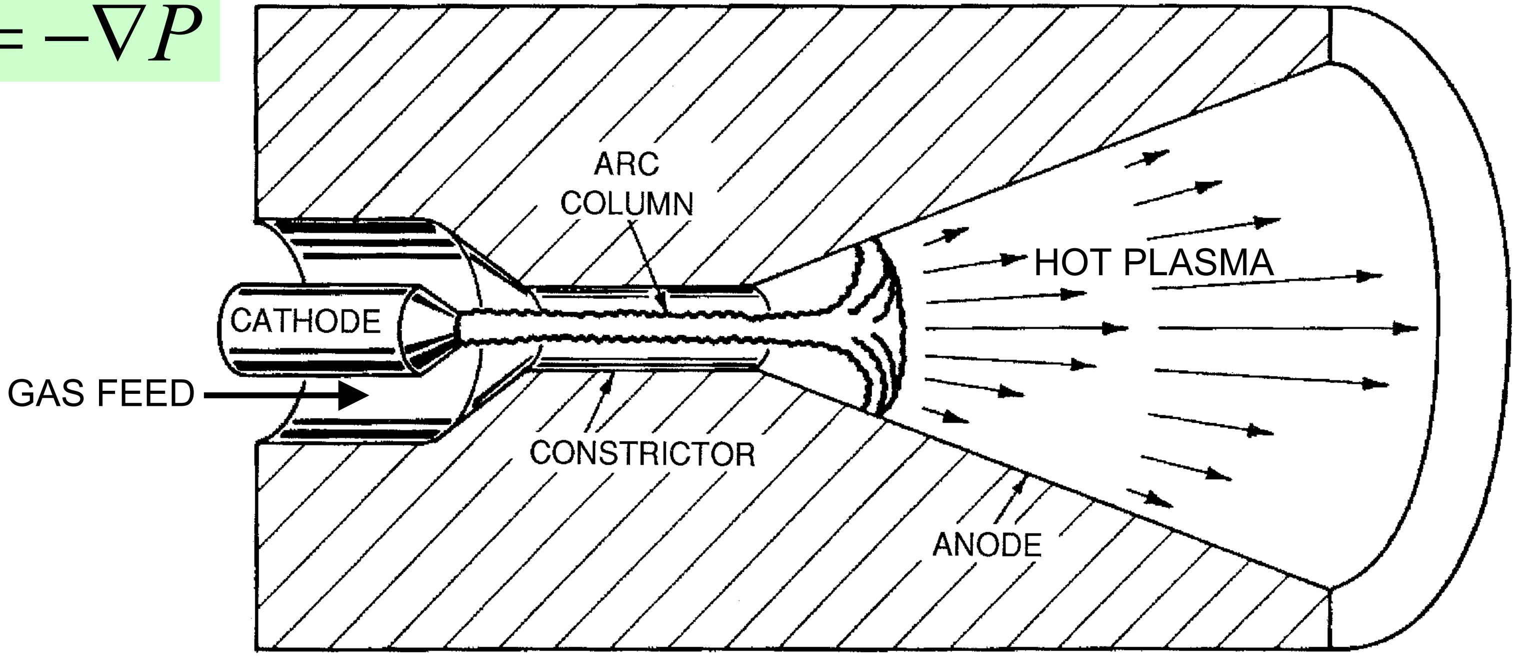
Plasma (Electric) Thrusters Come in Three Basic Varieties

- Electrothermal
  - Plasma pressure driven
  - Modest thrust, relatively low exhaust velocity
- Electrostatic
  - Voltage-gradient driven
  - Low thrust, high exhaust velocity
- Electromagnetic
  - Complicated electromagnetic driving forces
  - Modest thrust, modest exhaust velocity

Electrothermal Thruster

- Basic principle of electrothermal thrusters is to create a hot plasma that expands because of internal pressure.

$$\vec{F} = -\nabla P$$

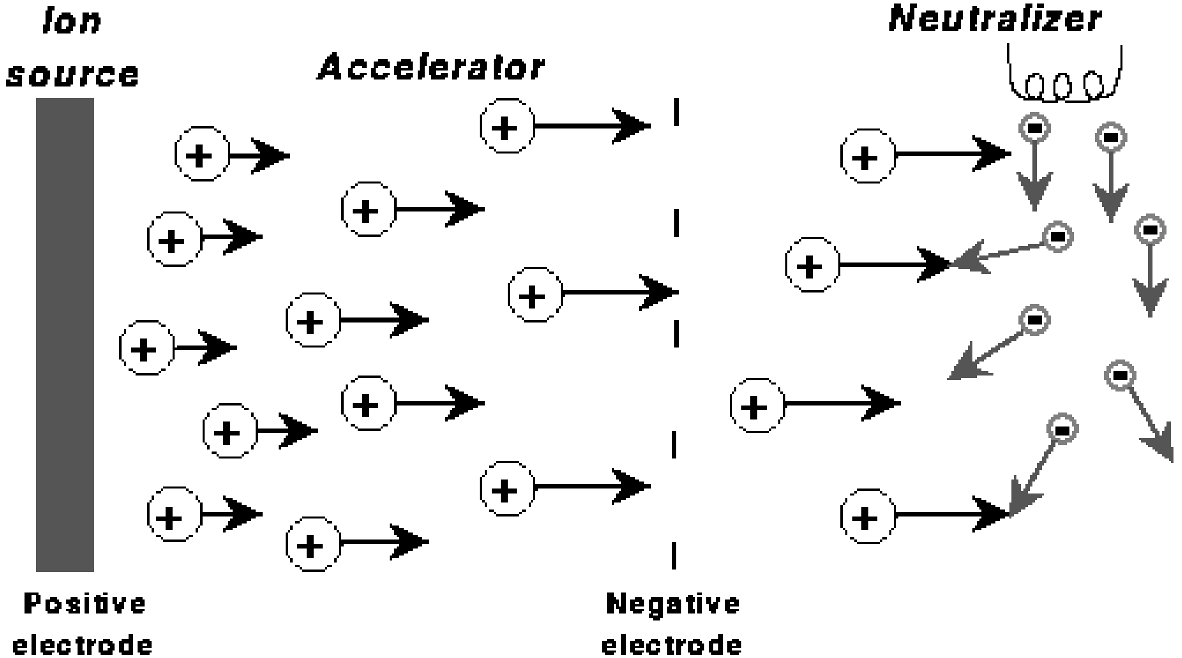


From Robert Jahn, Physics of Electric Propulsion (1968)

Electrostatic Thruster

- Basic principle of electrostatic thrusters is to cause ions to pick up energy by falling down a potential hill.

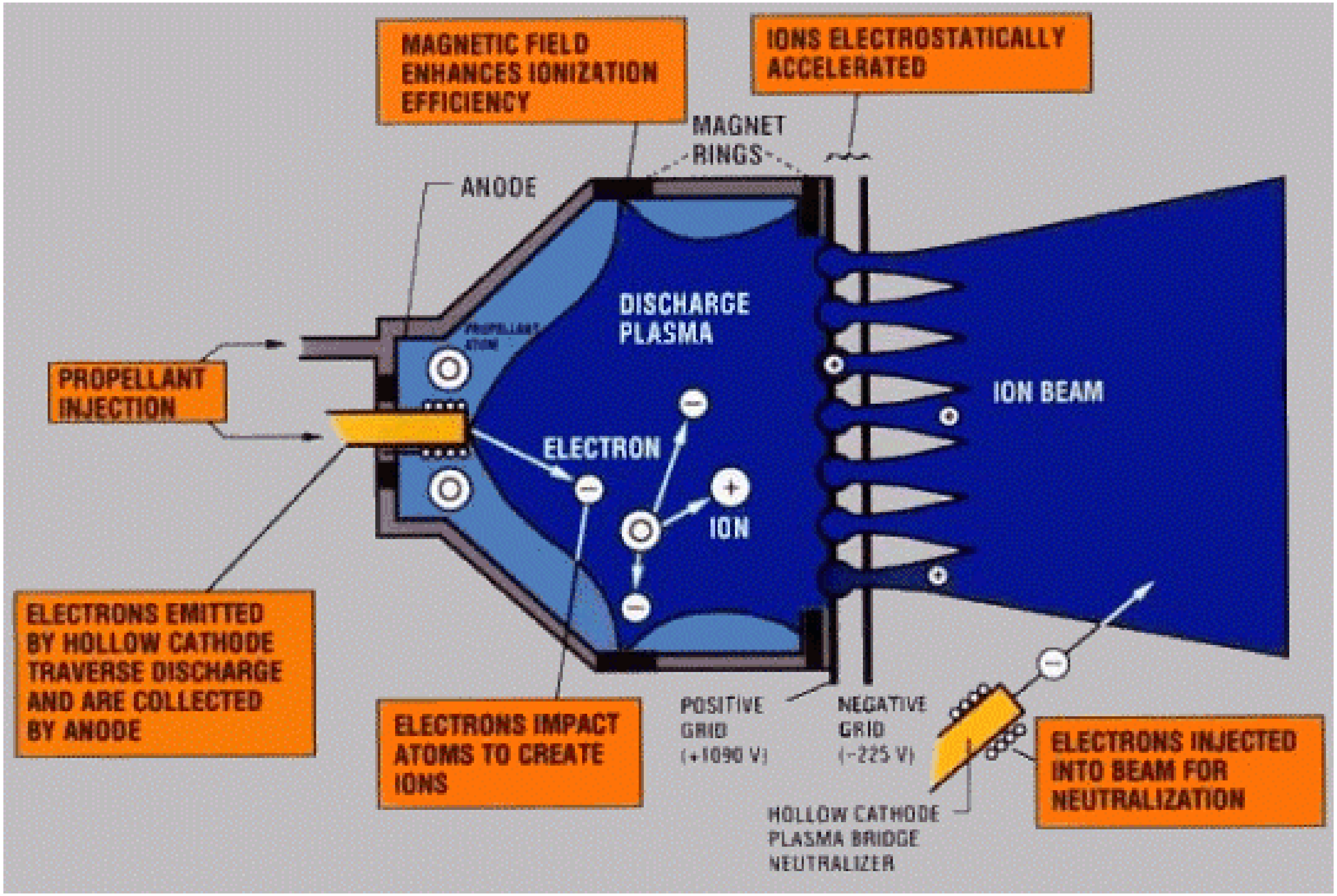
$$\vec{F} = q\vec{E} = -q\nabla\Phi$$



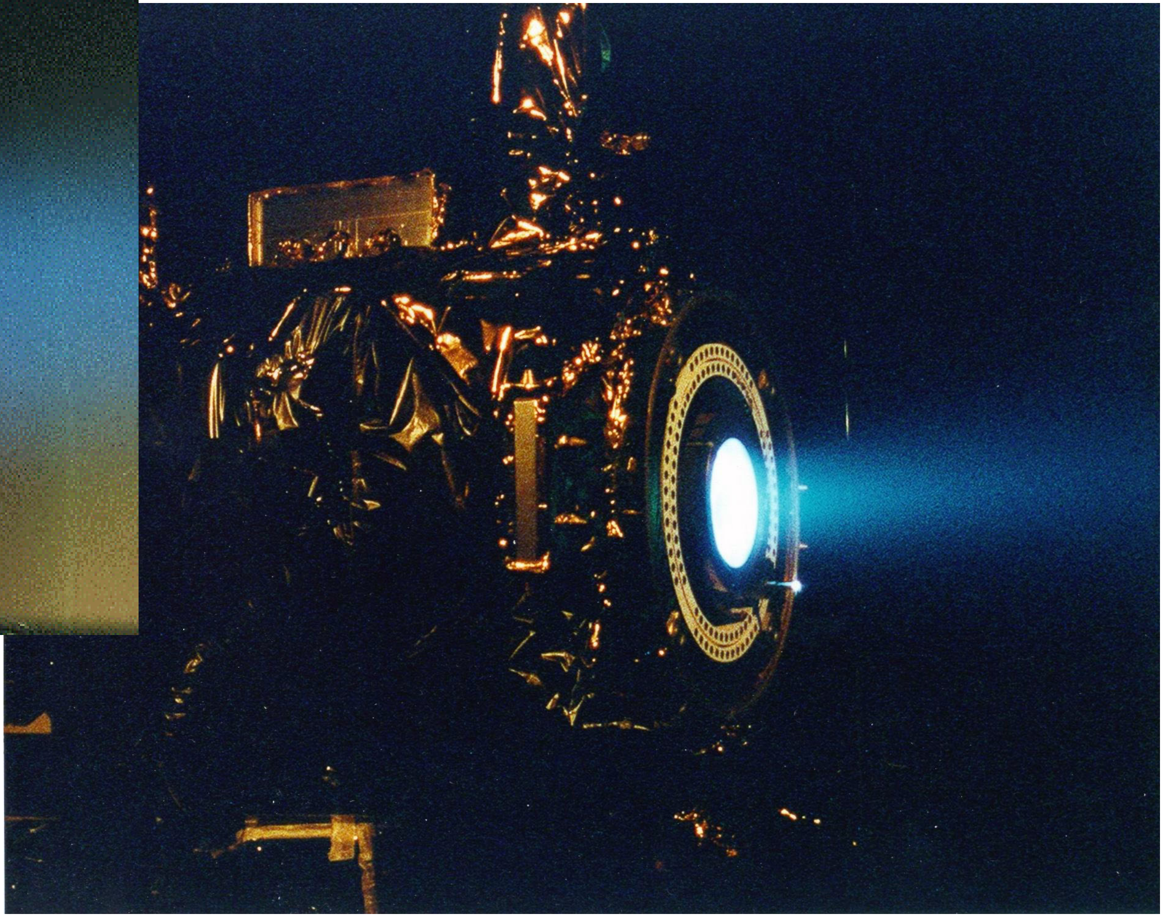
$$\Phi = V_+$$

$$\Phi = V_-$$

Exploded View of Electrostatic Ion Thruster



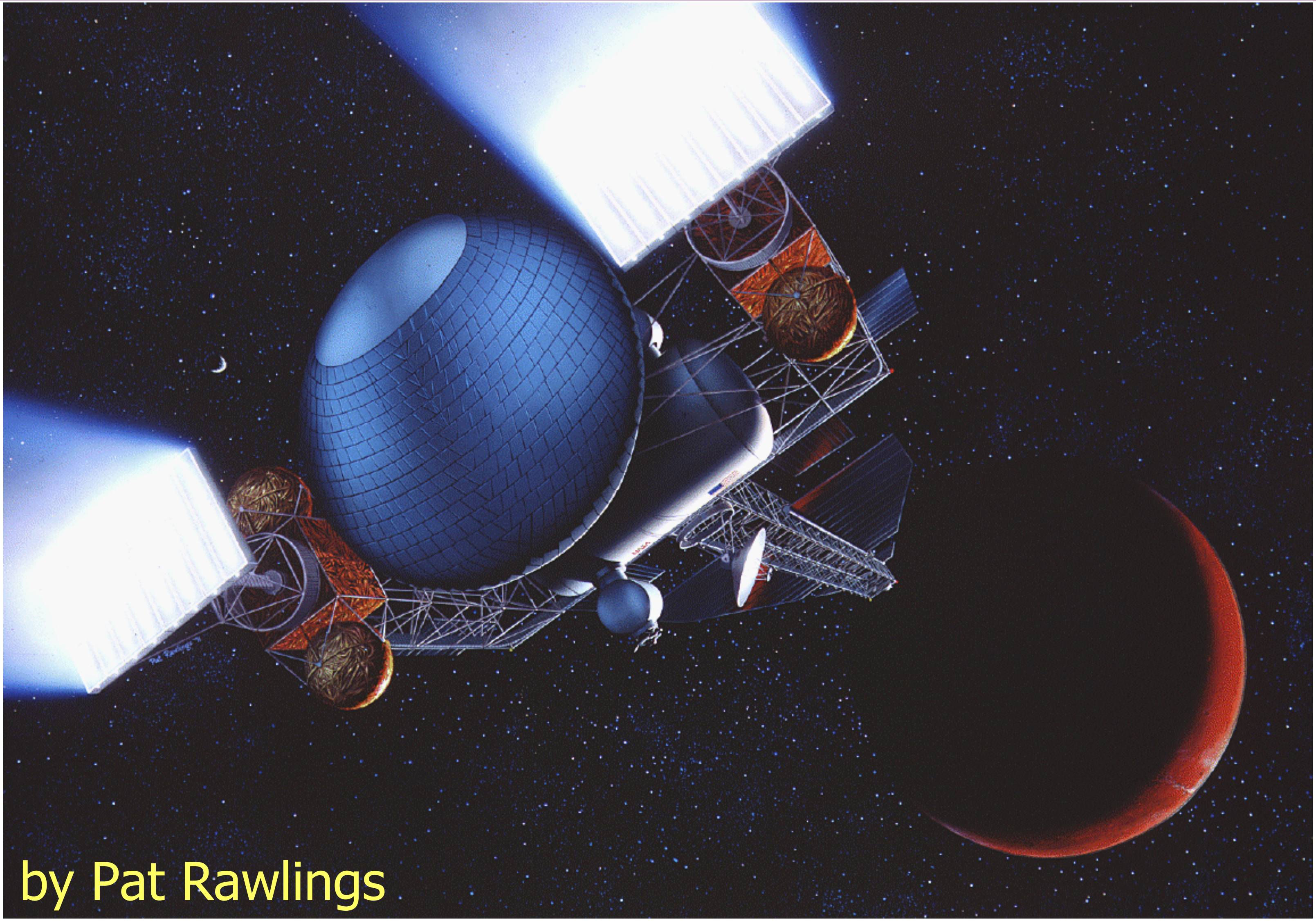
Xe Ion Thruster on Deep Space I (1998) Substantially Exceeded its Design Lifetime



Deep Space 1 Ion Thruster Parameters

Parameter	***Value***
Exhaust velocity	31 km/s
Grid voltage difference	1.28 kV
Power	2.3 kW
Thrust	93 mN
Mass flow rate	2.3 mg/s
Mass	8.3 kg
Propellant mass	88 kg
Thruster efficiency	0.62
Lifetime	8,192+ hours
Δv to spacecraft (486 kg)	4.5 km/s

Nuclear-Electric Propulsion (NEP) Conceptual Design Using Ion Thrusters



Electromagnetic Thrusters

- Electromagnetic thrusters depend on both electric and magnetic fields for their operation.
  - Can be steady-state or pulsed.
  - The presently most important varieties appear below.

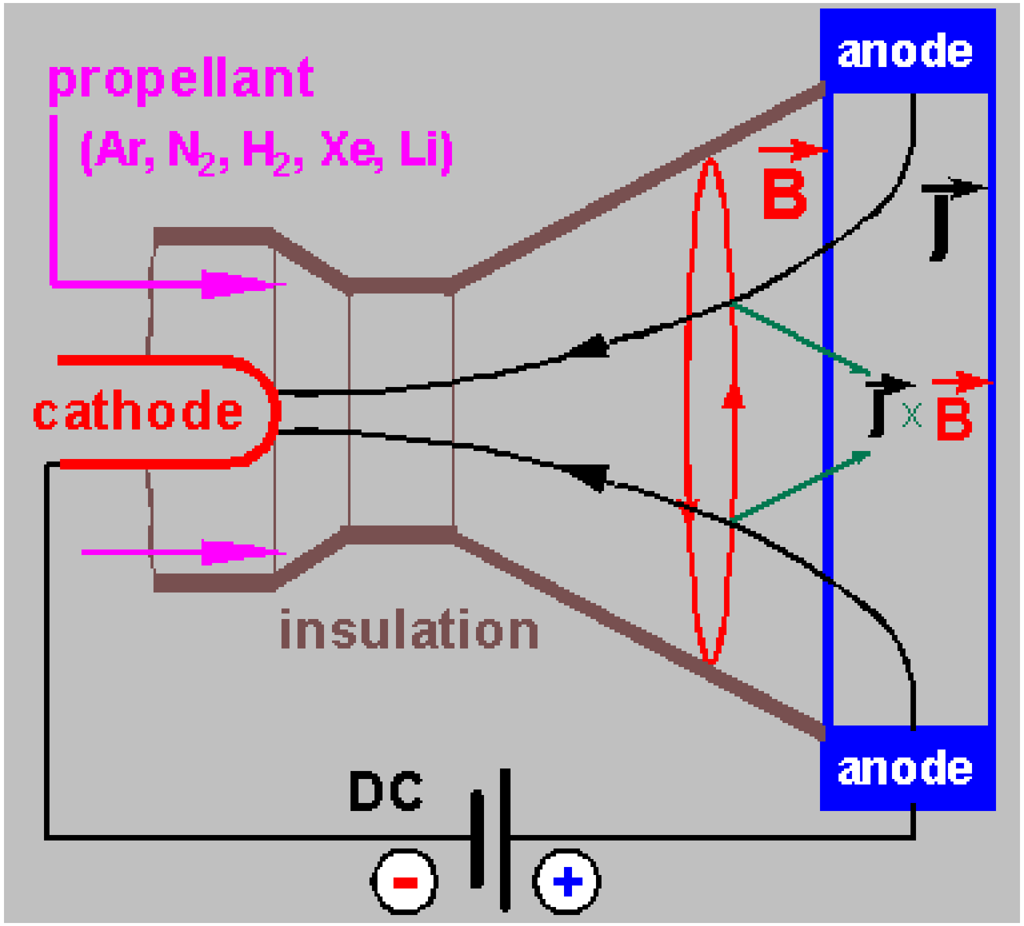
Thruster Type	*Key Operating Principle*
MPD (magnetoplasmadynamic)	J x B force on plasma
Hall (SPT or button)	Hall effect (E x B drift)
Pulsed-plasma	J x B force moving current
Pulsed-inductive	Radio-frequency wave induced current

Magnetoplasmadynamic (MPD) or Lithium Lorentz Force Thruster

- Basic principle of MPD thrusters is to utilize the force perpendicular to a current crossing a magnetic field.

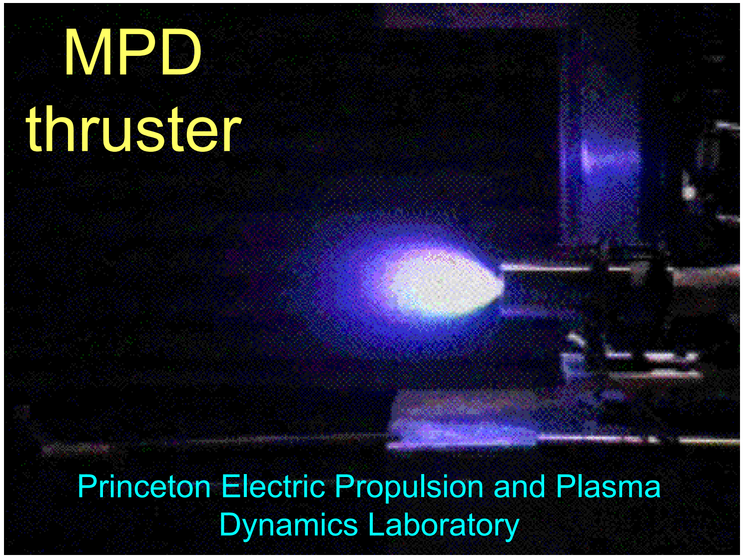
$$\vec{F} = \vec{j} \times \vec{B}$$

$$\vec{j} = nq\vec{v}$$



From University of Stuttgart's web page:
www.irs.uni-stuttgart.de/RESEARCH/EL_PROP/e_el_prop.html

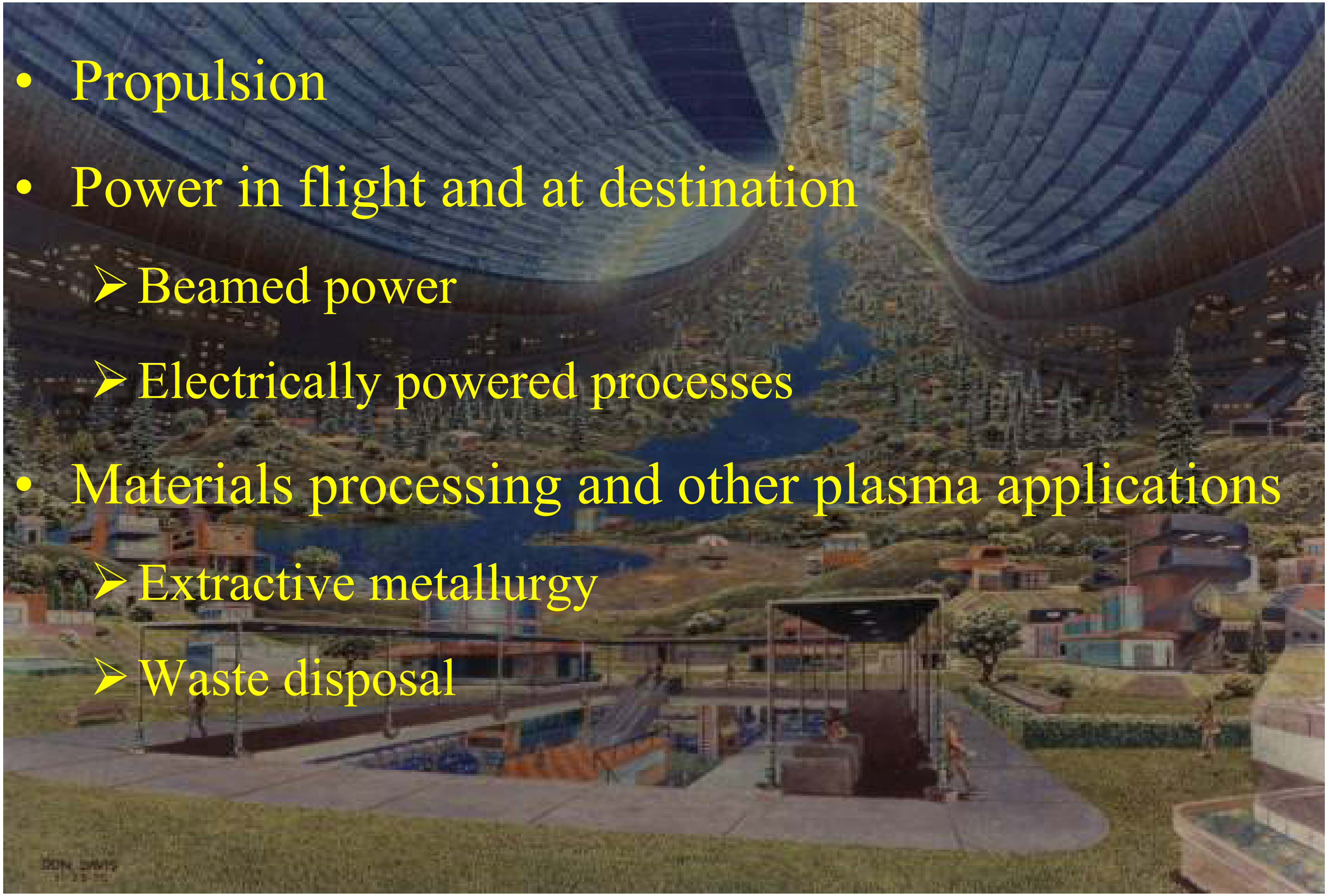
Electrodynamic Thruster Hardware Examples



Typical Electromagnetic Thruster Parameters

Parameter	*MPD*	*Hall*
Exhaust velocity	4 km/s	24.5 km/s
Mass flow rate	3.1 g/s	20 mg/s
Power	>100 kW	10 kW
Thrust	12.5 N	500 mN
Thruster efficiency	0.4	0.59
Lifetime	500+ hours	1000 hours

Carrying a Separate Power Source Gives Flexibility



- Propulsion
- Power in flight and at destination
  - ➢ Beamed power
  - ➢ Electrically powered processes
- Materials processing and other plasma applications
  - ➢ Extractive metallurgy
  - ➢ Waste disposal

Useful References

- Low-Thrust trajectories
  - Ernst Stuhlinger, *Ion Propulsion for Space Flight* (McGraw-Hill, New York, 1964).
  - Krafft A. Ehricke, *Space Flight: II. Dynamics* (Van Nostrand, Princeton, 1962).
- Plasma thrusters
  - Robert G. Jahn, *Physics of Electric Propulsion* (McGraw-Hill, New York, 1968).