Plasma Magneto-Shell Aerocapture for Manned Mars Missions and Planetary Deep Space Orbiters

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Why Plasma MagnetoShells

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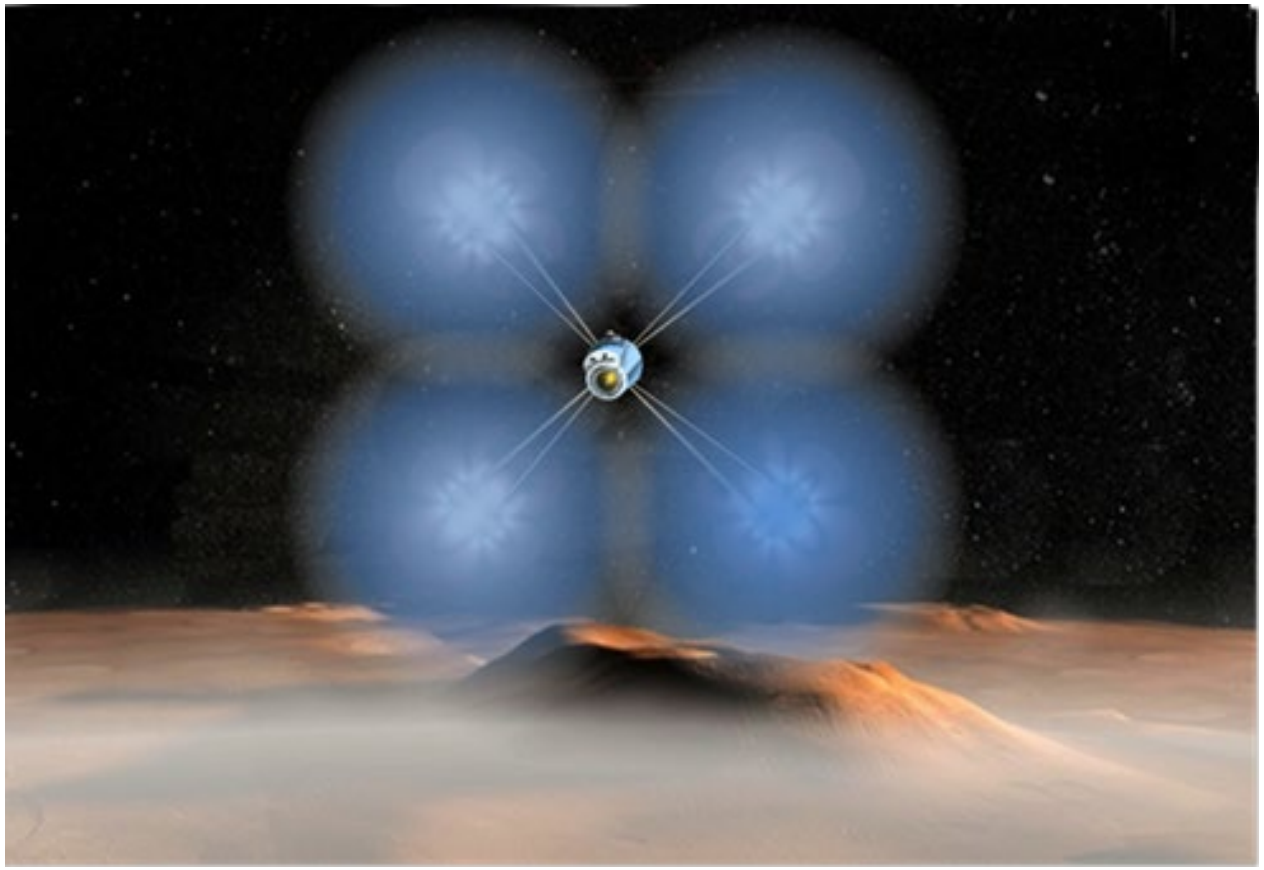
A Dynamic Plasma Parachute

Advantages

- Magnetoshell drag >> Aerodynamic drag
- Neutral-plasma >> Plasma-plasma drag
- Drag can be adjusted in seconds to changing environmental conditions by varying PMS scale via dipole field strength
- Same Delta-V savings as inflatables, but without heating concerns
- Lightweight, low-power, no need for HTSC

Challenges

- Very low TRL
- Testing a full-scale system will be quite challenging

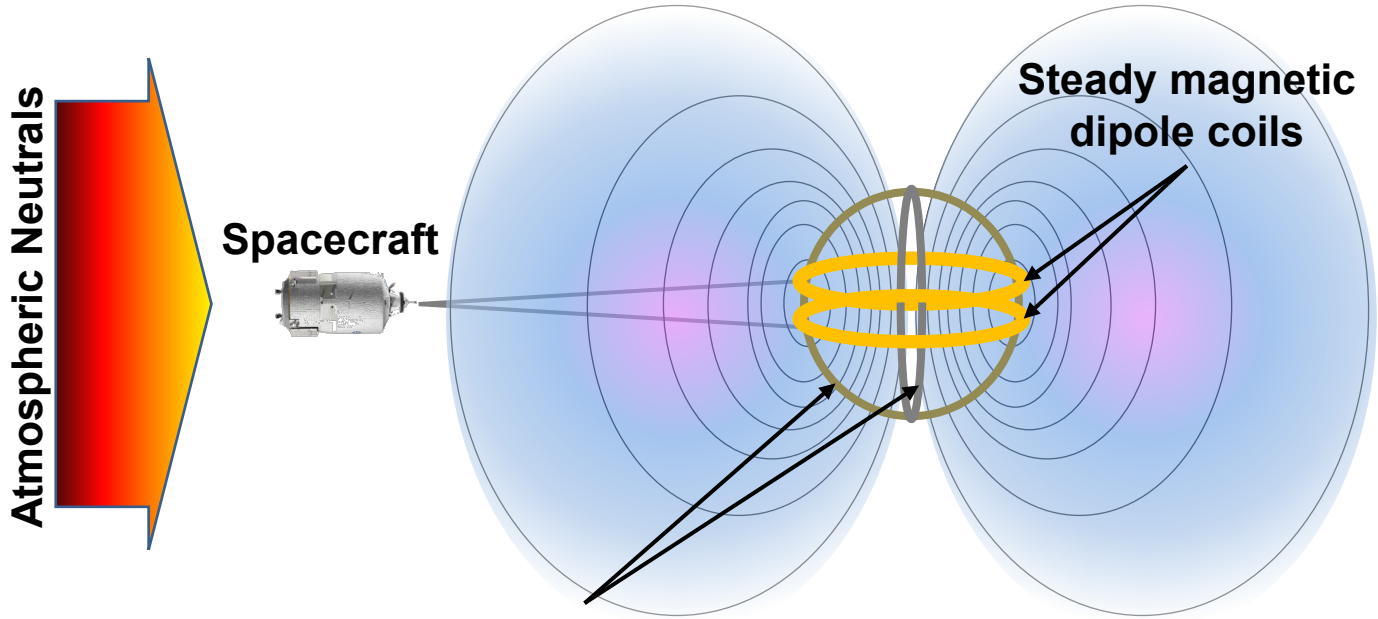


Artist's rendering showing several Plasma MagnetoShells deployed to steer and aerobrake spacecraft in the Martian atmosphere

The Plasma MagnetoShell (PMS) Concept

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1. PMS coil system is deployed on a tether downstream of spacecraft
2. A magnetized plasma ($T_{e,i}$ ~ 10 eV) is generated in a dipole field (B_{00}< 100G)
3. This plasma interacts with the incoming atmospheric neutrals through charge-exchange and ion collisions
4. These newly magnetized particles equilibrate in the dipole field transferring momentum to the coil and thereby decelerate the spacecraft
5. Plasma is sustained by thermalization of incoming directed energy
6. Aerobraking drag can be turned down or increased as needed.

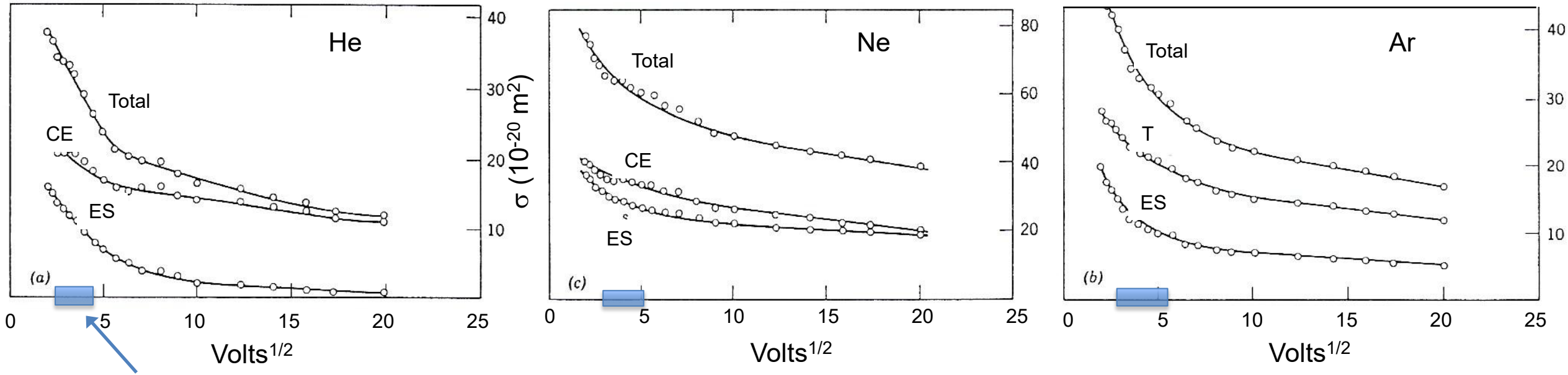


Rotating Magnetic Field (RMF) coils with oscillating currents phased at 90°

The RMF (similar to an induction motor) induces a large current in a background plasma. Fed by incoming neutrals, this current expands, forming a large, magnetized dipolar plasma.

PMS Interactions with Planetary Neutrals

Spacecraft deceleration is achieved primarily through charge exchange (CEX) interactions between the magnetized thermal ions in the Plasma MagnetoShell with atmospheric neutrals as this has a larger cross section than elastic collisions in most cases

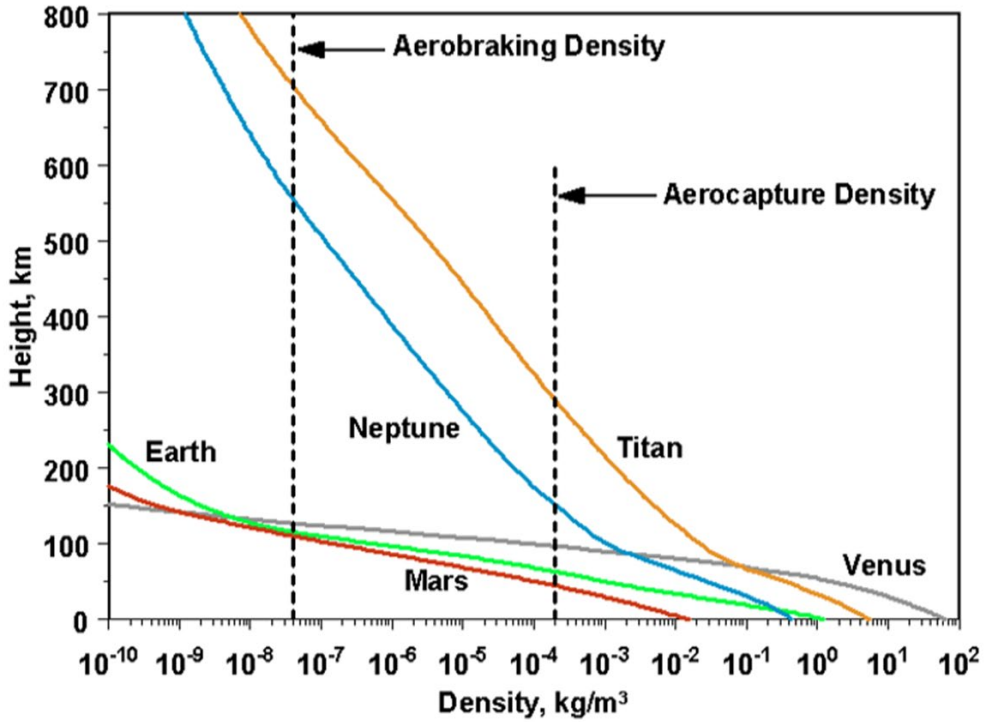


Expected range of plasma T (eV)$^{1/2}$

Experimental values for elastic scattering (ES), charge exchange transfer (CE), and the sum of the two for Helium, Neon and Argon ions as a function of the square root of the ion energy (eV) in their parent gases. (From McDaniel,E.W., J.B.A. Mitchell, and M.E. Rudd, (1993) Atomic Collisions: Heavy Particle Projectiles, Wiley, New York)

PMS Has Several Unique Advantages

- PMS operates at high altitude with much lower densities than braking systems thereby avoiding risky low altitude “weather”
- The structural load on sensitive components like solar panels is kept to safe levels
- frictional heat is deposited into the plasma rather than the spacecraft which helps to sustain the PMS.



Comparison of density profiles among the planets and Titan

Planet	Radius (10^6 m)	Orbital Vel. (m/s)	Orbital Per. (hr.)	Alt. where ρ ~4×10^{-8} kg/m^{-3} (km)	Principal Gases (%)
Earth	6.38	7,900	1.4	112	N2 [78] O2 [21] Ar [1]
Mars	3.4	3,549	1.7	115	CO2 [95] N2 [3] Ar [1]
Venus	6.05	7,327	1.4	125	CO2 [96] N2 [3]
Jupiter	71.5	42,078	3.0	350	H2 [90] He [10]
Saturn	60.3	25,066	4.2	950	H2 [96] He [3]
Uranus	20.6	16,764	2.1	550	H2 [83] He [15] CH4 [2.5]
Neptune	24.8	16,563	2.6	560	H2 [80] He [19] CH4 [1]
Titan	2.57	1,865	2.4	710	N2 [96] CH4 [3.5] H2 [0.5]

Candidate planetary and atmospheric data for PMS aerobraking

Scaling and Key Physics

Collision length: The incoming neutral densities must be low enough so that charge exchange will occur within the PMS of scale L.

$$\lambda_{CE} = \frac{1}{n_{neu}\,\sigma_{CE}} \leq L$$

Ion Magnetization: The magnetic field and velocity must yield magnetized CEX ions (and source ions) with gyro-orbits less than the size of the PMS.

$$\Omega_i = \frac{e\,B}{m_i n \sigma_{i-n} v_i} > 1$$

Bohm confinement timescale: Unlike most astrophysical plasmas, this plasma is neutral collision dominated, leading to Bohm diffusion and was observed in experimental testing.

$$\tau_n \sim \frac{2\mu_0}{3\eta_i\,\beta} \ln\left(\frac{r}{R_0}\right) r^2$$

Thermal equilibrium: Thermal equilibrium controls plasma density and effective radius thus drag. Incoming particles result in hot ions which heat electrons. Ionization cools electrons, The relaxation rate between the ions and electrons is given by:

$$\nu_{e-i} = \frac{2 n_i \sigma_T \ln\Lambda}{\pi^{1/2}} \left(\frac{m_e}{m_i}\right) \left(\frac{k_B T_e}{m_e}\right)^{-3/2}$$

Plasma Density: The plasma densities must be high enough that the PMS is collisional during entry, otherwise neutral particles are unimpeded. Using the empirical cross section for charge exchange for a given atomic species and electron temperature, the charge exchange reaction rate equation can be calculated for each radial position averaged over a chord length.

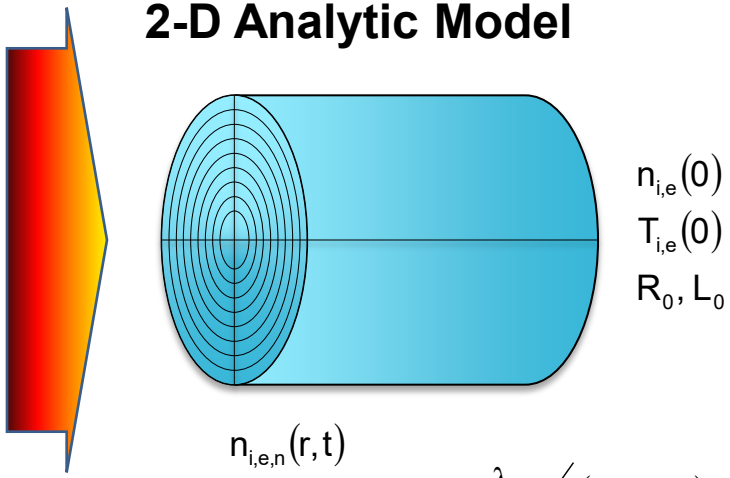
$$n_{CEX} = \sigma_{CEX}(T_e) n_n n_e \frac{V_0}{L_0} \Delta t$$

$$n_{ion} = \sigma_{ion}(T_e) n_n n_e \frac{V_0}{L_0} \Delta t$$

2-D Time Dependent Model

- Critical physics are the confinement and transport
- Low-Beta dipole (R^3) scaling is utilized
- Transient model finds equilibrium plasma states
- Equilibrium performance is found for all altitudes and fields

2-D Analytic Model



1. Assume r,z 2-D symmetry
2. Transiently evolve equilibrium plasma conditions with uniform free stream
3. Find total force and particle confinement

Confinement

$$n(r) \sim n(R_0)\left(\frac{R_0}{r}\right)^3$$

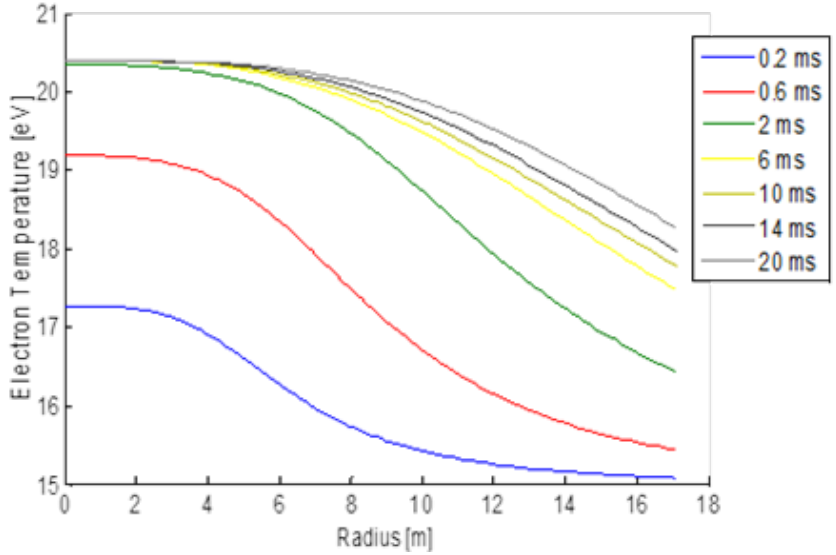
$$\lambda_{CE} = \frac{1}{n_{n0}\sigma_{CE}} \qquad r_i = \frac{mU_0}{eB}$$

$$\pi r_i < \lambda_{CE} \le L_0$$

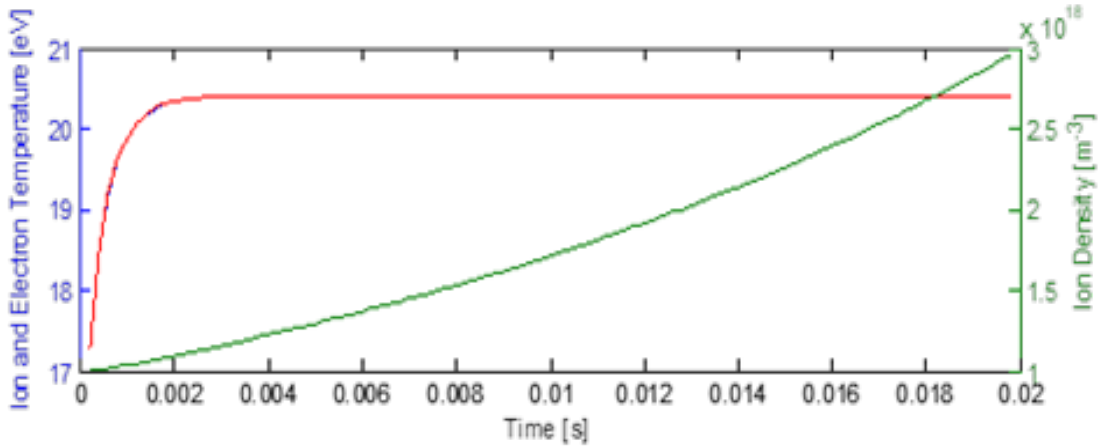
- Ion gyroradius (r_i) and charge exchange mean free path (l_{CE}) are less than characteristic length
- Particle must stay confined for a minimum of one-half of orbit

PMS Analytic Model Results

- Given sufficient time, T_i equilibrates reflecting the average directed energy of the incoming flow.
- Temperature also relaxes to a peaked profile quite quickly.
- Thermal equilibrium occurs in a few msec at the core, and the radial T profile evolves in less than a second
- Density profile evolves on the plasma confinement timescale which can be minutes



Radial and temporal relaxation of a 20 eV incoming flow. Shown is the case for Venus orbital insertion with a 10 km/s insertion speed



Ion and Electron Equilibration times are ~1 ms, while ion equilibration may take minutes. Shown is Venus with a 10 km/s insertion.

Particle-Based 2D model of Neutral Flow Interaction with the PMS

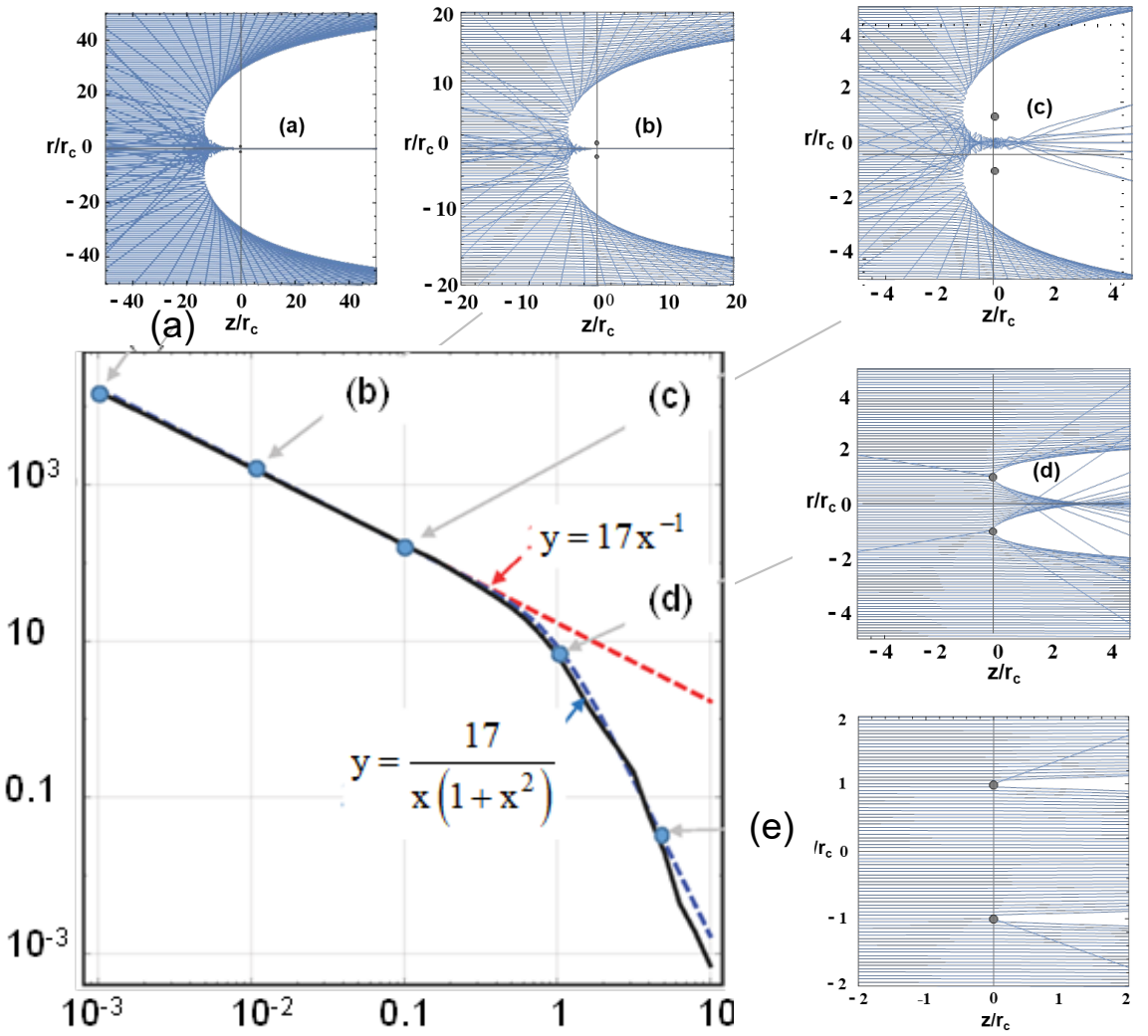
The drag force can be several thousand times larger than the area intercepted by the dipole coil itself.

These values however are only obtained with the largest magnetic dipole fields as the rest of the parameters that characterize the drag scaling are determined by location and velocity of the spacecraft

$$\frac{F_{drag}(PMS)}{F_{drag}(Coil)} = \frac{2F_{drag}}{\rho_{neu} v_{neu}^2 \pi r_c \delta}$$

Drag force on the PMS normalized to that intercepted by the dipole coil area. (The coil thickness δ is assumed to equal to $0.1r_c$)

Particle trajectories

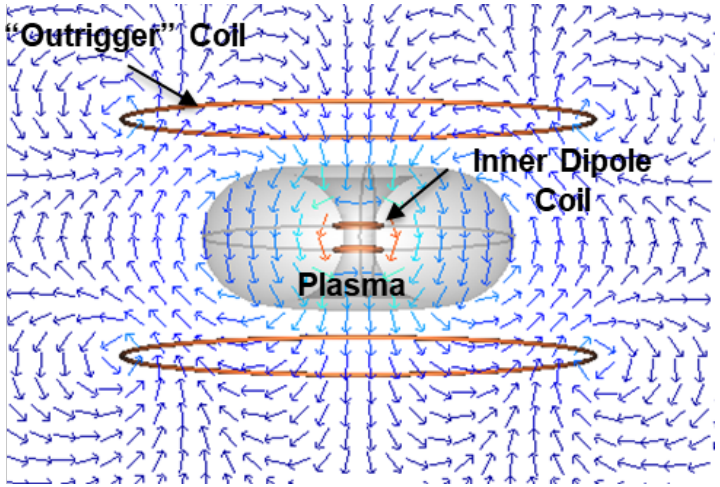


Ratio of the gyroradius based on the neutral flow energy to that of the coil radius.

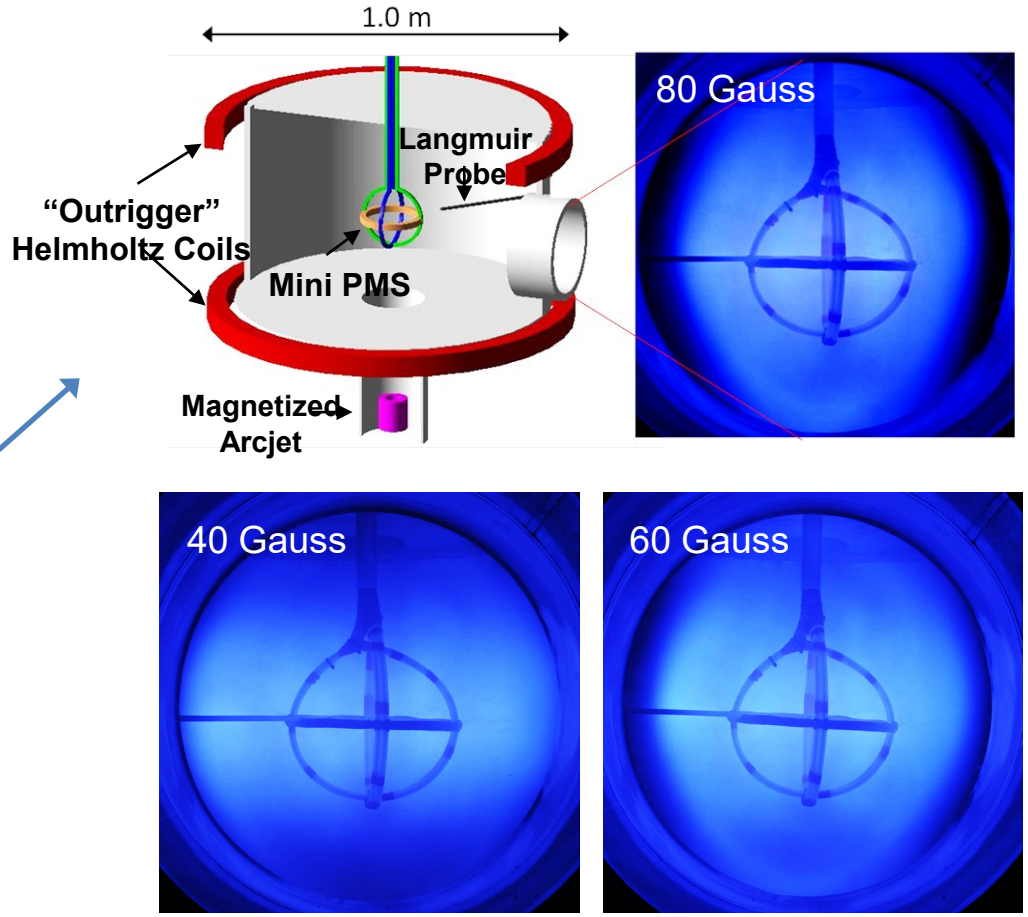
$$\frac{r_{Li}}{r_c} = \frac{m_{neu} v_{neu}}{e B_0 r_c}$$

Optimized Magnetic Configuration for PMS

- **Transverse orientation of PMS dipole (w.r.t. neutral flow) maximizes interaction cross-section**
- **PMS scale was controlled by magnitude of "Outrigger" dipole field**
- **An axial magnetic field as low as 10 Gauss limited the plasma expansion and avoided contact with vacuum chamber boundary**



PMS system with additional "outrigger" coils. Magnetic field line vectors reflect plasma toroidal currents driven by RMF.



Schematic of the PMS inside cylindrical vacuum chamber. (Images) Argon plasma created by PMS and confined by outrigger coils at various magnetic field strengths placed external to the vacuum chamber (red coils on schematic).

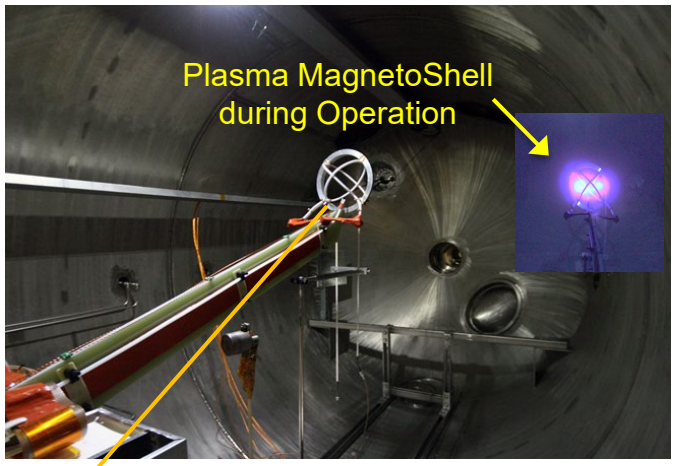
Experimental Demonstration

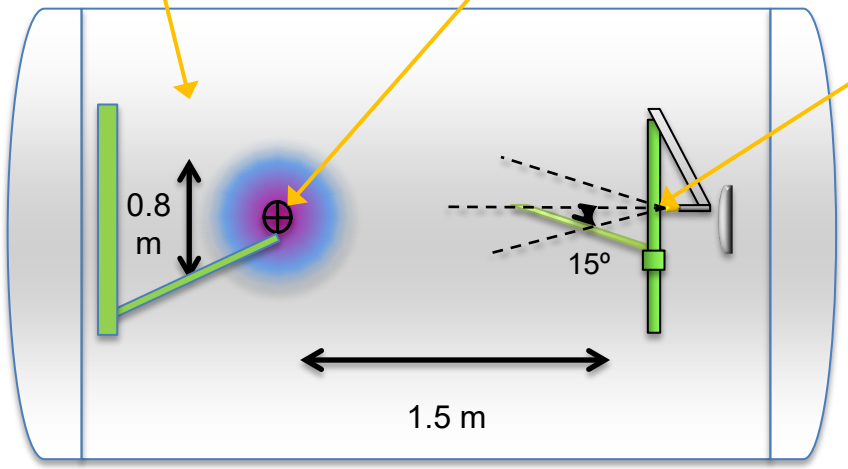
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Thrust Stand

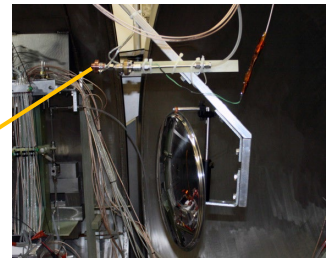


Dipole and RF Antenna on Boom Mounted to Thrust Stand





Arcjet Injector





Argon propellant
2 ms discharge

Methodology

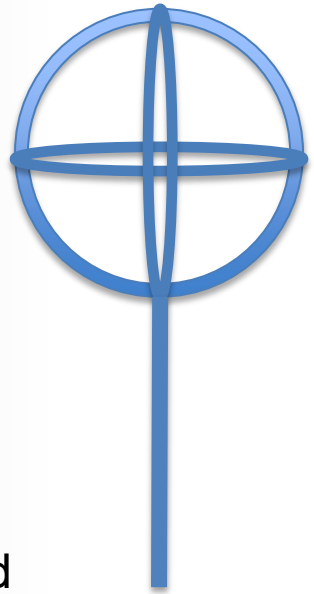
- Use MSNW 4m x 2m vacuum chamber 23,000 l/s pumping to maintain spacelike conditions
- Employ Argon arcjet (few % ionization) to deliver a high velocity (~ 2 km/s) neutral gas surrogate
- Construct a small scale (~10 cm) dipolar magnet with Rotating Magnetic Field (RMF) to produce a magnetized Argon plasma
- Mount the coil set with a gas and electrical feed on a boom attached to a thrust stand
- Measure the increase in drag force induced on the structure with and without the PMS operating from the Argon jet stream

Thrust Stand Results

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Process

1. Measure velocity from Langmuir Probe
2. Measure drag impulse for various pulsed conditions
3. Reduce uncertainty with 5-10 discharge per condition
4. Calculate effective neutral density from jet impulse
5. Calculate effective drag force from impulse and average on-time, subtracting neutral force
6. Calculate effective collection area from all measured



Effective Area

- Perpendicular neutral area is 20 cm^2
- Effective Plasma MagnetoShell area assumes circular, uniform cross section and 100% capture

Operating Condition	Measured Drag	Effective Area	Relative Drag
Plasma MagnetoShell activated with directed arcjet-heated Argon neutral flow	220 mN	2.3 m^2	**1150**
Directed arcjet-heated neutral flow only	190 μN	0.02 m^2	1

Summary:

An Ar Plasma MagnetoShell was generated that intercepted an Ar supersonic neutral jet, demonstrating both charge exchange, entrainment, and a >1000X increase in drag.

PMS Power Requirements

The RMF power, P_{RMF}, needed to sustain the plasma magnetoshell in this configuration is given by:

$$P_{RMF} = \int \eta \, j_\theta^2 \cdot dVol$$

j_θ is the azimuthal current density from the RMF.

Flux conservation demands that $B(r) \sim B_0 R_0^2/r^2$, so that one has for j_θ:

$$j_\theta = \frac{1}{\mu_0}\frac{dB}{dr} = \frac{-2B_0}{\mu_0}\frac{R_0^2}{r^3}$$

B_0 is the magnetic field at the center of the dipole coil.

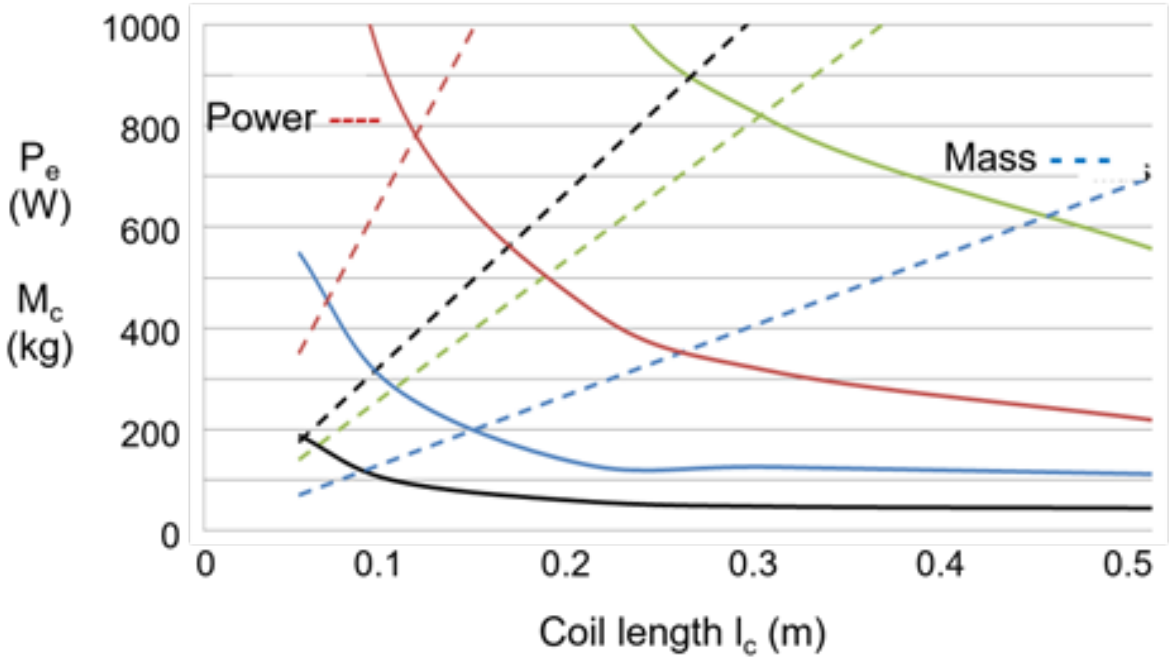
Substituting and integrating one has:

$$P_{RMF} = \frac{4\eta}{\mu_0^2} B_0^2 R_0^4 \int_{R_0}^{r>>R_0} \frac{4\pi}{r^4} dr \quad = \quad \frac{16\pi\eta}{3\mu_0^2} B_0^2 R_0$$

To maximize drag force (~ r^2) per unit RMF power, one wants the largest PMS at the lowest field consistent with ion gyro-orbit constraints (i.e. $r_i < r_{PMS}$)

PMS Optimization and Design

Power and Mass scaling with length for a 250 G coil



Data is for copper and steady heating.

Red – 1 m Diam. 0.25 m thick;

Black – 0.5 D, 0.1 m t;

Green – 1 m D, 0.1 m t;

Blue – 0.5 m D, 0.1 m t.

Summary of PMS parameters for a Neptune orbiter and Mars 60t spacecraft insertion

Plasma MagnetoShell Design Parameter	Optimized Configuration for Neptune	Optimized Configuration for Mars
Dipole Coil Radius (material)	2 m	2.5 m
Total Dipole Coil Mass	81 kg	190 kg
Total Battery and SEP Mass	72 kg	250 kg
Dipole Coil Length	3.5 cm	50 cm
Dipole Coil Width	3.5 cm	1 cm
Effective Aerobraking Radius	9 m	21 m
Total Mass with 30% margin	210 kg	690 kg
Equivalent Aeroshell Weight	885 kg	~20,000 kg

Comparison of Experiment and Requirements for Manned Mars Insertion

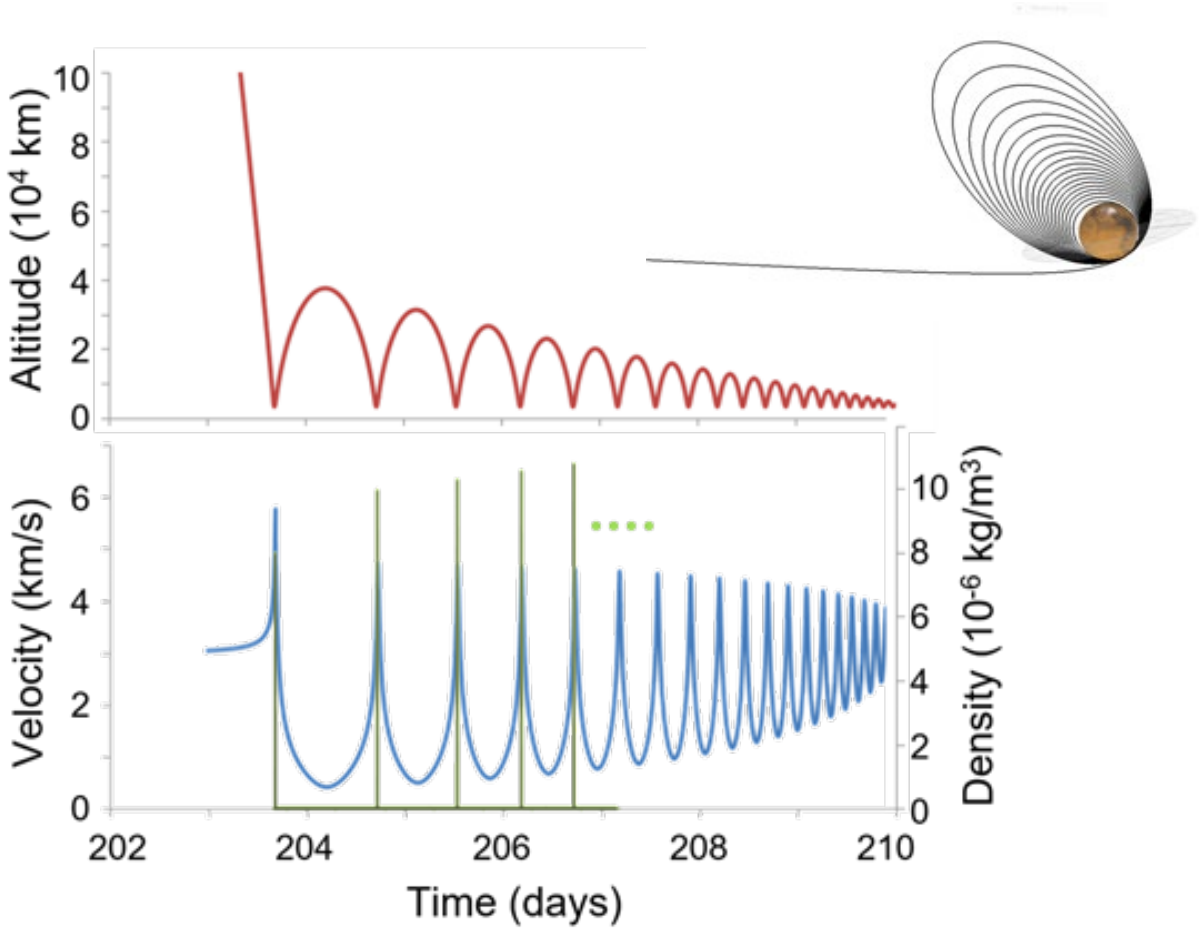
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Parameter	Mars Insertion	Experiment
Velocity	7000 m/s	700 m/s
Incoming Mass	44 amu	40 amu
Neutral Density	1e18 m^{-3}	3e18 m^{-3}
Peak Field	100 Gauss	300 Gauss
Edge Field	0.04 Gauss	3 Gauss
PMS Outer Radius	50 m	1 m
Dynamic Pressure	1 N/m2	0.05 N/m2
Deceleration Force	15 kN	0.15 N
Ion Temperature	15 eV	10 eV
Stored Field Energy	150 J	1 J
RF Power/Energy	25 kW	4 J
r_i / λ_{CE}	0.02	0.01
r_i / R_0	0.02	0.3

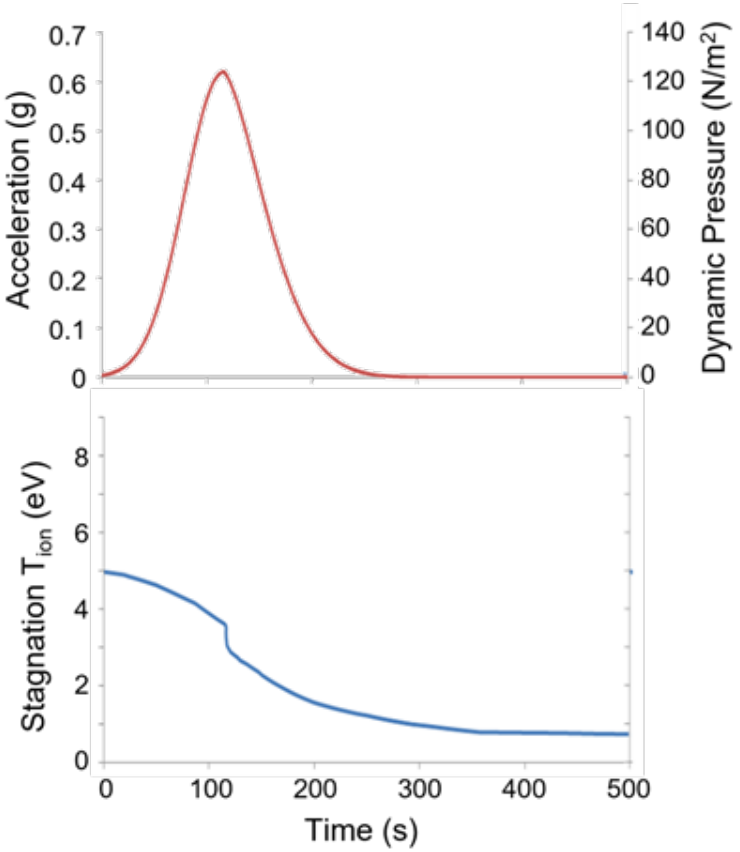
PMS Manned Mars Mission Orbit Analysis

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Optimal Mars insertion into Martian atmosphere based on Copernicus calculation and PMS optimized parameters.



Spacecraft altitude, velocity and Martian atmospheric mass density during orbital periods. Time is from LEO departure



(Top) Close up of the PMS dynamic deceleration and pressure for the initial insertion. (Bottom) Incoming equivalent ion temperature

PMS Aerocapture Has Huge Mission Mass, Time, and Cost Benefits

- **Lower Mass** – 1 MT of PMS hardware replaces 20 MT of heatshields
- **Controllable** – Can be adjusted dynamically to meet atmospheric conditions
- **Magnetic** – Capable of high velocity entry well beyond any physical heatshield
- **Compatible** – Easily integrated with existing propulsive and entry technologies for infusion