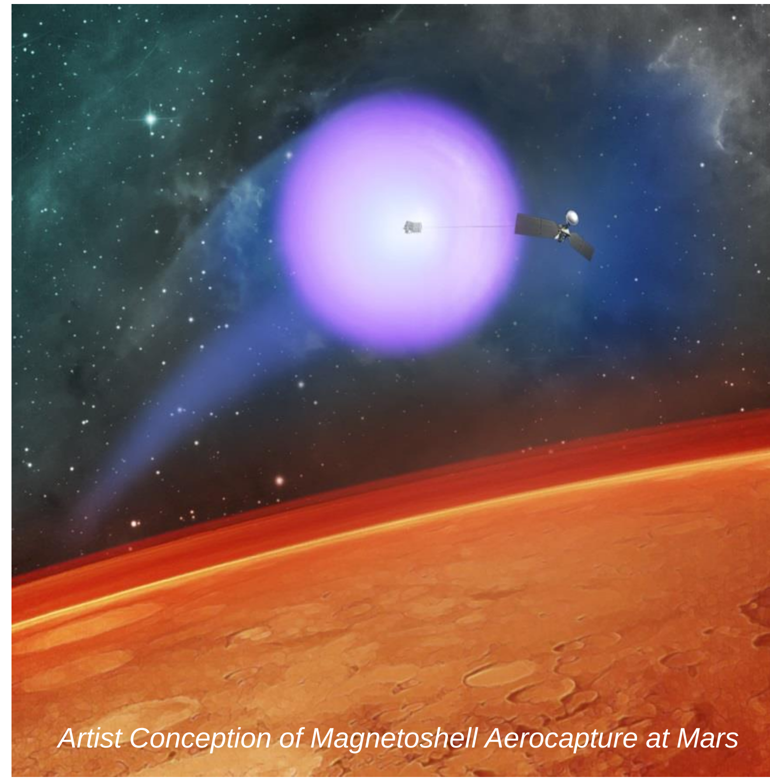
Magnetoshells

Plasma Aerocapture for Manned Missions and Planetary Deep Space Orbiters

Argon Magnetoshell at MSNW during Phase I testing



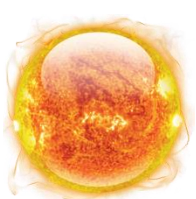
Artist Conception of Magnetoshell Aerocapture at Mars

NIAC Spring Symposium
Chicago, Il.
March 12, 2013

Dr. David Kirtley
Dr. John Slough
Dr. Anthony Pancotti

Spaceflight is Hard

- More propellant and energy is used to slow down and orbit at a destination than to get there
- Unlike on Earth, using drag to slow down is difficult and risky
- Thermal protection, Aerobraking, and Aerocapture are major subjects of the Decadal Survey, NRC review, and Strategic Plan
- Magnetoshells may replace or augment these technologies



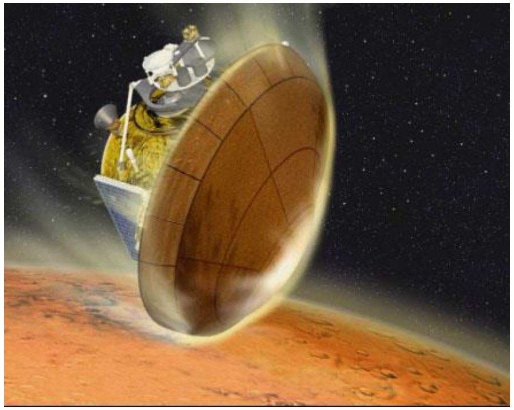
Aerocapture

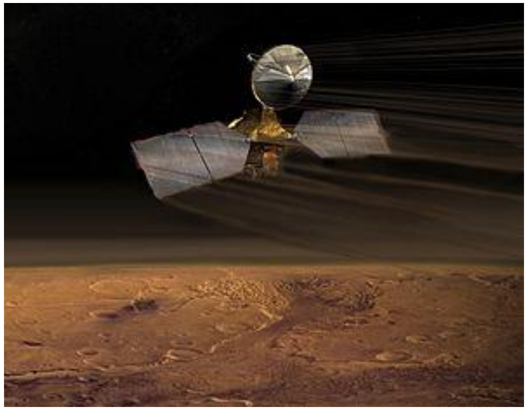
Aerocapture uses a planet's ambient atmosphere to decelerate

- Spacecraft decelerate using hypersonic viscous forces
- Aerobraking takes multiple passes and has demonstrated mission benefits (1 MT propellant for Magellan)
- Aerocapture is hyperbolic, one-pass, and the only way to manned Mars missions

The issues

- Typically heavy
- Atmosphere must be know before arrival
- **Dynamically unstable!**
- Low TRL technology (and lots of development underway)





Why Magnetoshells ?

- Aerocapture has huge mission mass, time, and radiation benefits
- Magnetoshells should be even lighter, lower risk, and suitable for deep space orbiters

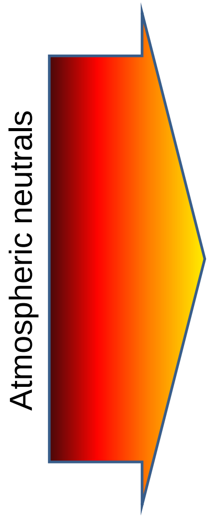
Advantages

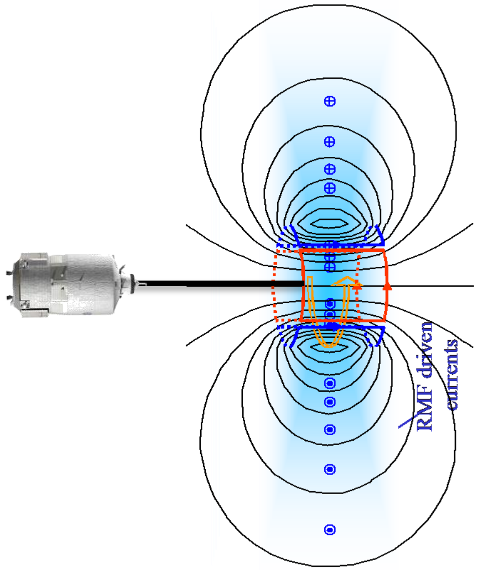
- ➢ Magnetoshell drag >> Aerodynamic drag
- ➢ Neutral-plasma drag >> Plasma-plasma drag
- ➢ Drag can be controlled electronically in real time
- ➢ Enormous Mission Delta-V Savings
- ➢ Lightweight, low-power, no superconductors

A Magnetoshell doesn't deflect gas like an aeroshell or plasma like a magnetic decelerator. It captures the hypersonic neutral gas through collisional processes. The momentum of the charge-exchanged gas is absorbed by the magnetic structure.

Magnetoshell

A Dynamic Plasma Parachute

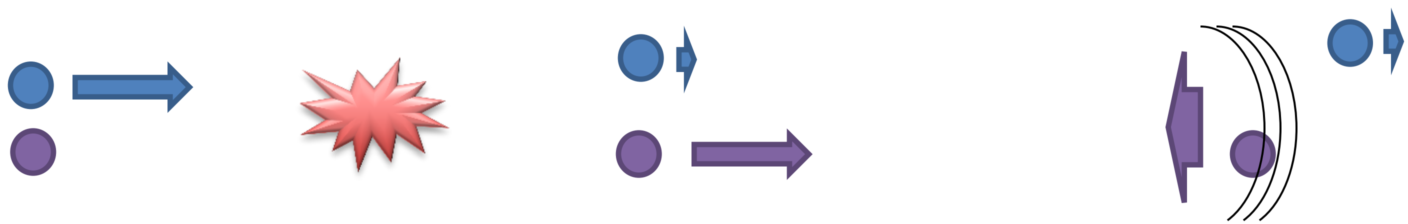




1. A spacecraft deploys Magnetoshell hardware on a 50 meter tether
2. A 500 Gauss magnetic dipole field is formed
3. A low-temperature, magnetized plasma is injected into that field
4. Plasma shell captures atmospheric neutrals through charge-exchange
5. As the captured particles equilibrate, they decelerate the spacecraft
6. Plasma is fueled and heated from captured planetary neutrals
7. Aerobraking drag can be turned off at any time (or increased)

Key Concept

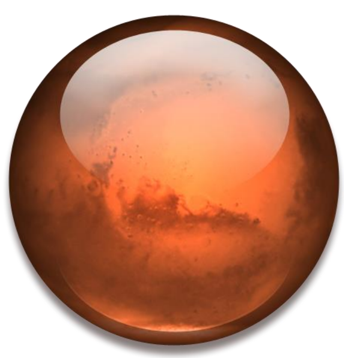
Entrainment of Neutrals in a Magnetized Plasma



High energy neutrals enter magnetoshell

Magnetoshell ions charge exchange with neutral gas

New magnetized ion brakes via magnetic coil structure



- Charge exchange collisions dominate
- Ionization sustains Magnetoshell
- Incoming energy powers Magnetoshell

Replace the physical shell with a controlled, magnetized plasma

Aerobraking Missions

Magnetoshells should be used to replace Aerobraking and augment Aerocapture

- Venus Sample Return
  - Magnetoshells shed 8 km/s, reducing TPS to purely descent heat shield
  - 1000 kg reduction for 1500 payload

- Manned Martian
  - 40 MT insertion shield, total 204 MT reduction for 30 MT payload
  - Mission is now two low-risk phases, orbiting and then descent

- Neptune Orbiter
  - Mission now possible – No nuclear reactor required
  - 1500 kg orbiter and Triton lander – Aerocapture for insertion

Mission	Mars Manned	Venus Sample Return	Neptune Orbiter
Incoming Velocity	5.5 km/s	10.6 km/s	26.7 km/s
Neutral Molecular Weight	43.4 amu	43.4 amu	2.5 amu
Ion Average Weight	15.0 amu	14.6 amu	1.6 amu
Directed Neutral Energy	7.0 eV	25.5 eV	9.4 eV
Aerocapture Max Density	1.3E19 #/m^3	3E18 #/m^3	3.5E18 #/m^3
Entrance Altitude	200 km	300 km	2000 km

The Benefits of Light, Reliable Magnetoshells for Aerocapture

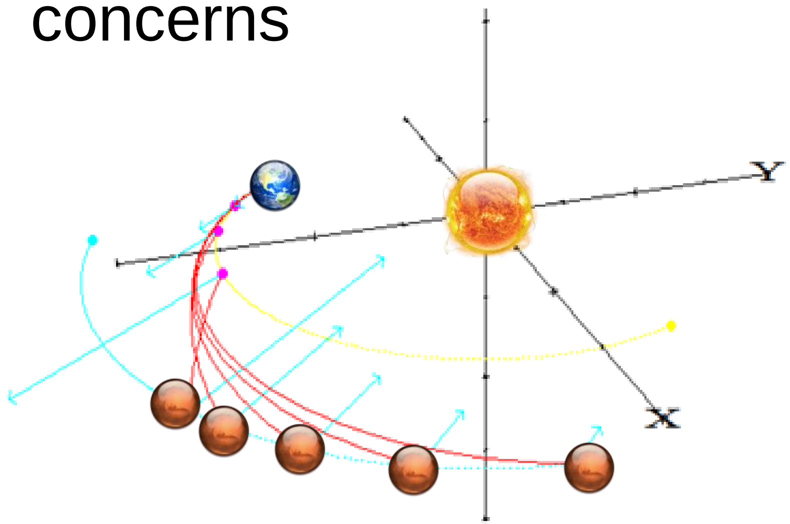
NASA Mission	Cost Benefit	Mission Risk Benefit
Venus Sample	-70% $/kg (EP) +4.6 km/s	Large cost savings, no insertion shield
Manned Mars	-$1.8 B per mission	Heat shield mass, manned mission risk
Jupiter Icy Moons	Mission possible without NEP	Dynamic atmosphere not known, full benefit unknown
Titan Lander	-84% $/kg +4.5 km/s	Now possible
Neptune Tour	-90% $/kg +6.0 km/s	Dynamic atmosphere not known

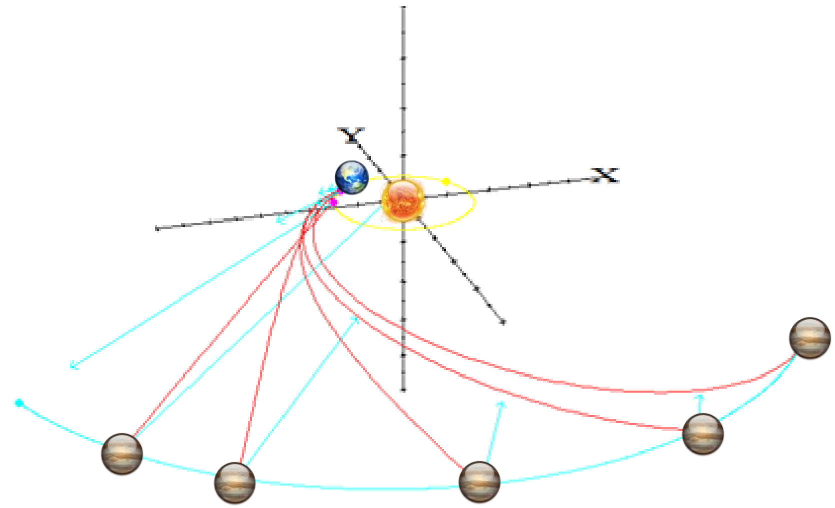




Hyperbolic Trajectories

- Decelerating ΔV at the target dramatically reduces mission mass, propellant, etc as shown.
- Conversely, for the Holman ΔV the transit time can be halved, halving radiation, risk, and operational costs.
- Magnetoshells have appear to have no heat flux or soak concerns





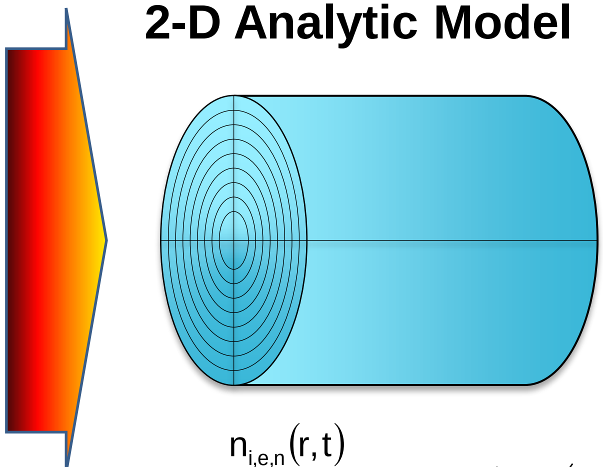
Time (Days)	Earth ΔV (km/s)	Mars ΔV (km/s)
30	20.9	~~24.5~~
60	9.1	~~13.8~~
90	5.4	~~9.3~~
120	3.8	~~6.5~~
150	3.1	~~4.4~~

Time (Days)	Earth ΔV (km/s)	Jupiter ΔV (km/s)
100	65.5	~~83.5~~
250	20.9	~~32.8~~
500	10.6	~~13.6~~
750	8.9	~~7.3~~
1000	9.1	~~5.6~~

Scaling and Key Physics

- Critical physics are the confinement and transport
- Low-Beta dipole (R^3) scaling is utilized
- A complicated, High-Beta plasma enhances scaling but is not required
- Transient model finds equilibrium plasma states
- Equilibrium performance is found for all altitudes and fields

2-D Analytic Model



$n_{i,e}(0)$

$T_{i,e}(0)$

$R_0,\ L_0$

$$V_0,\ n_0,\ T_\infty \rightarrow \begin{matrix} n_{i,e,n}(r,t) \\ T_{i,e}(r,t) \\ \sigma_{ion,CEX,ex}(r,t) \\ D_\perp(r,t) \end{matrix} \rightarrow \begin{matrix} \lambda_{CE}/r_i\,(r,B_0,n_0) \\ F_D(B_0,n_0) \end{matrix}$$

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

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

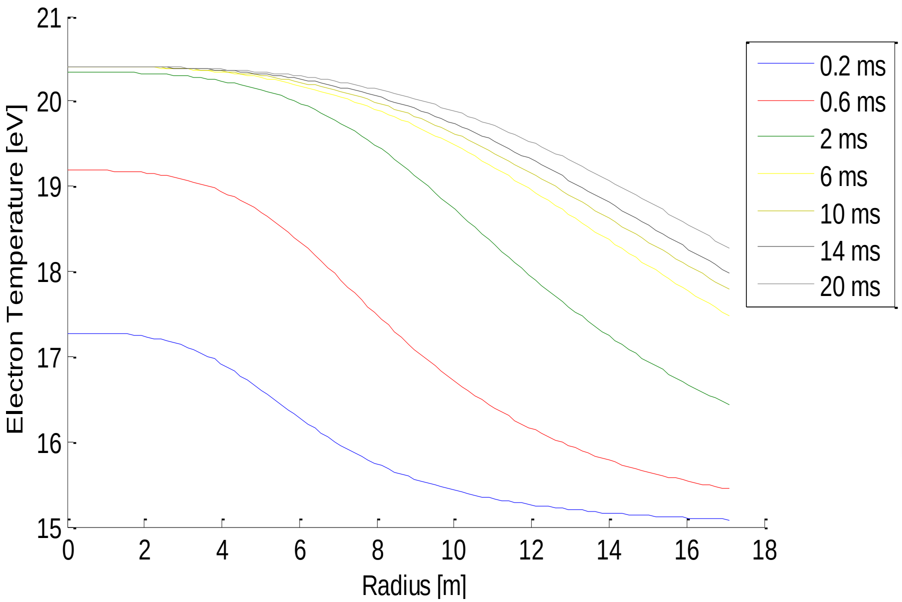
$$\lambda_{CE} = \frac{1}{n_{n0}\sigma_{CE}} \qquad r_i = \frac{mU_0}{eB}$$

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

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

Transient Model

- Transient model initialized with uniform temperature, steady flow, R^3 density.
- Density increases with ionization, decreases with diffusion from outer boundary
- Ion temperatures increase with CEX (to free stream), electrons cooled by ionization
- 10X increase in density ~100 ms

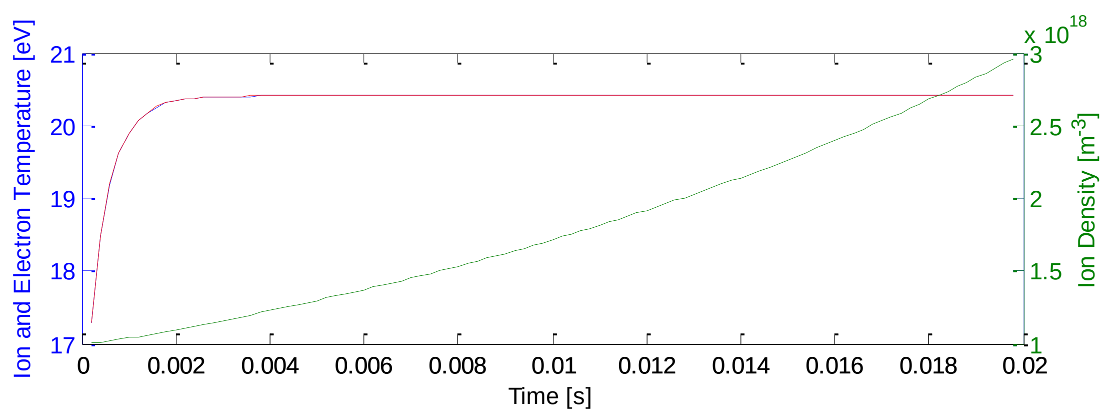


$$n_{CEX} = \sigma_{CEX}(T_e)\, n_n n_e \frac{V_o}{L_o}\Delta t \qquad D_{Bohm} \propto \frac{k_B T}{B}$$

$$n_{ion} = \sigma_{ion}(T_e)\, n_n n_e \frac{V_o}{L_o}\Delta t \qquad D_{\perp} \propto \eta_{\perp}\frac{k_B T}{B^2} \propto \frac{m_i k_B T^{1/2}}{B^2}$$

$$\nu_{s-s} = \frac{2 n_s \sigma_T \ln\Lambda}{\pi^{1/2}}\left(\frac{m_e}{m_i}\right)\left(\frac{k_B T_e}{m_e}\right)^{-3/2}\left[1/s\right]$$

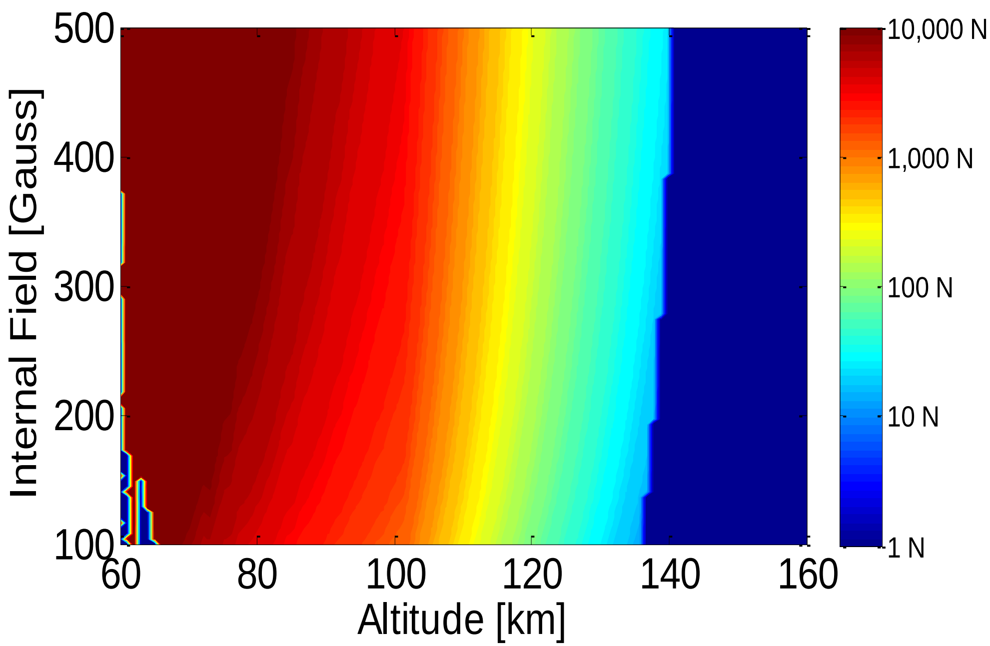
Model Details: Empirical cross sections, Bohm and classical diffusivities (full range of likely restivity), Maxwellian equilibrium, Fokker-Planck relaxation rates, local qausi-neutrality, uniform chord (z) temperature and density. Fixed, uniform radial grid. Proper temporal and radial resolution.



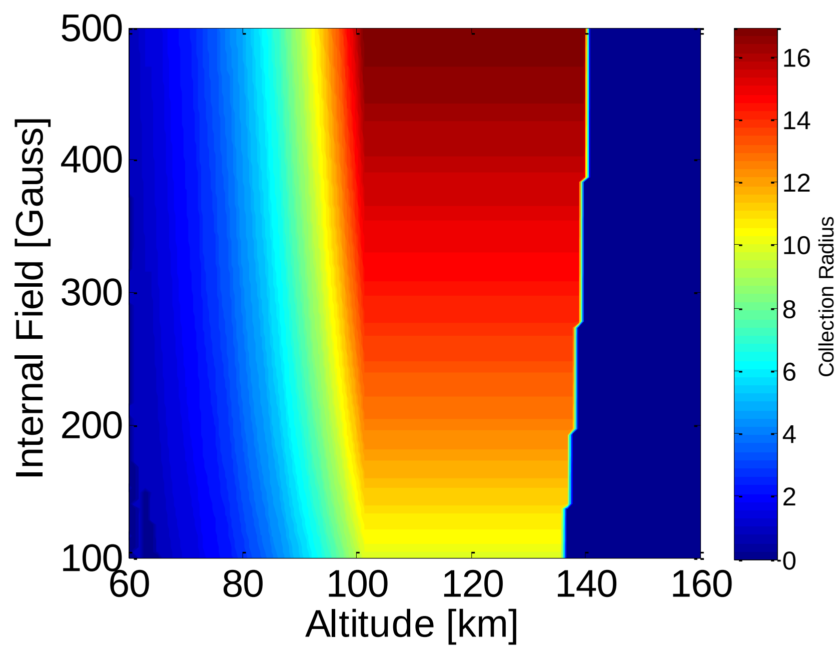
Ion and Electron Equilibration times are ~1 ms, while ion equilibration may take minutes. Shown is Venus, 10 km/s insertion.

Mars Scaling

- Martian deceleration is excellent
- At 120 km
  - Drag force of 1 kN
  - Effective drag radius of 15 meters with 1 meter antenna
  - All power, temperature, and plasma provided by incoming flow (after startup)



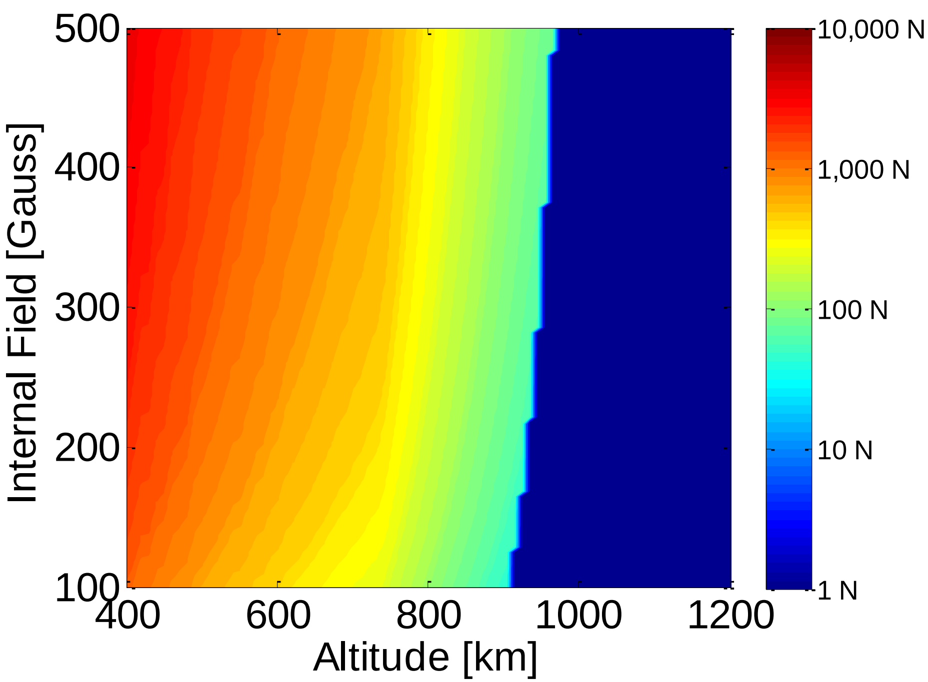
Martian Drag Force. Logarithmic drag force for equilibrium Magnetoshell and increasing magnetic field.



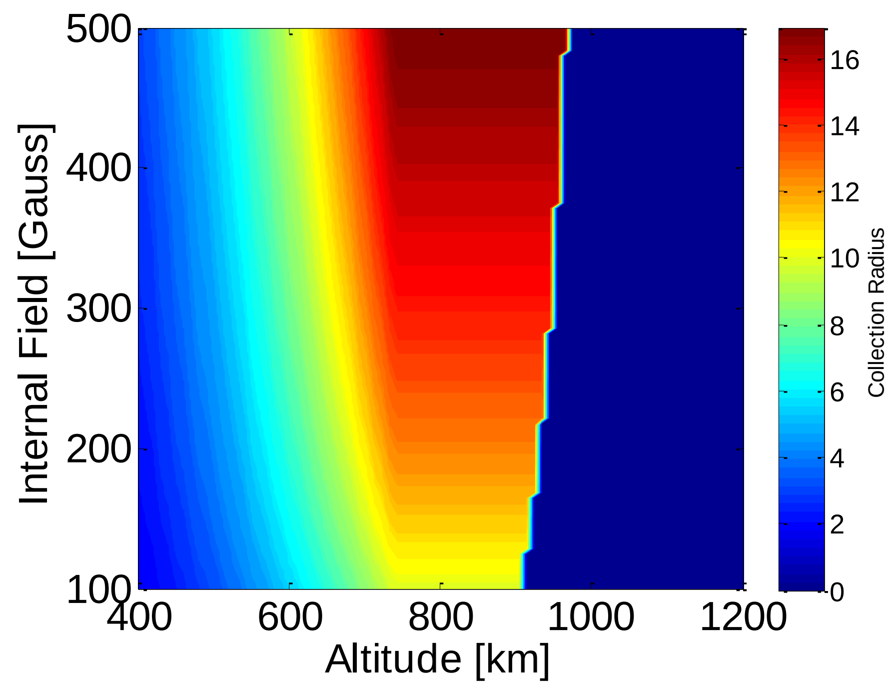
Effective Collection Radius. Outer radial boundary of confined CEX.

Neptune Scaling

- Neptune Aerocapture and then Aerobraking
- At 1000 km
  - Drag force of 100 N
  - Effective drag radius of 17 meters with 1 meter antenna
  - All power, temperature, and plasma provided by incoming flow (after startup)



Neptune Drag Force. Logarithmic drag force for equilibrium Magnetoshell and increasing magnetic field.

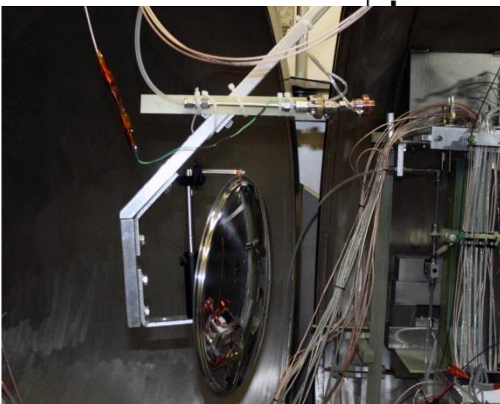


Effective Collection Radius. Outer radial boundary of confined CEX.

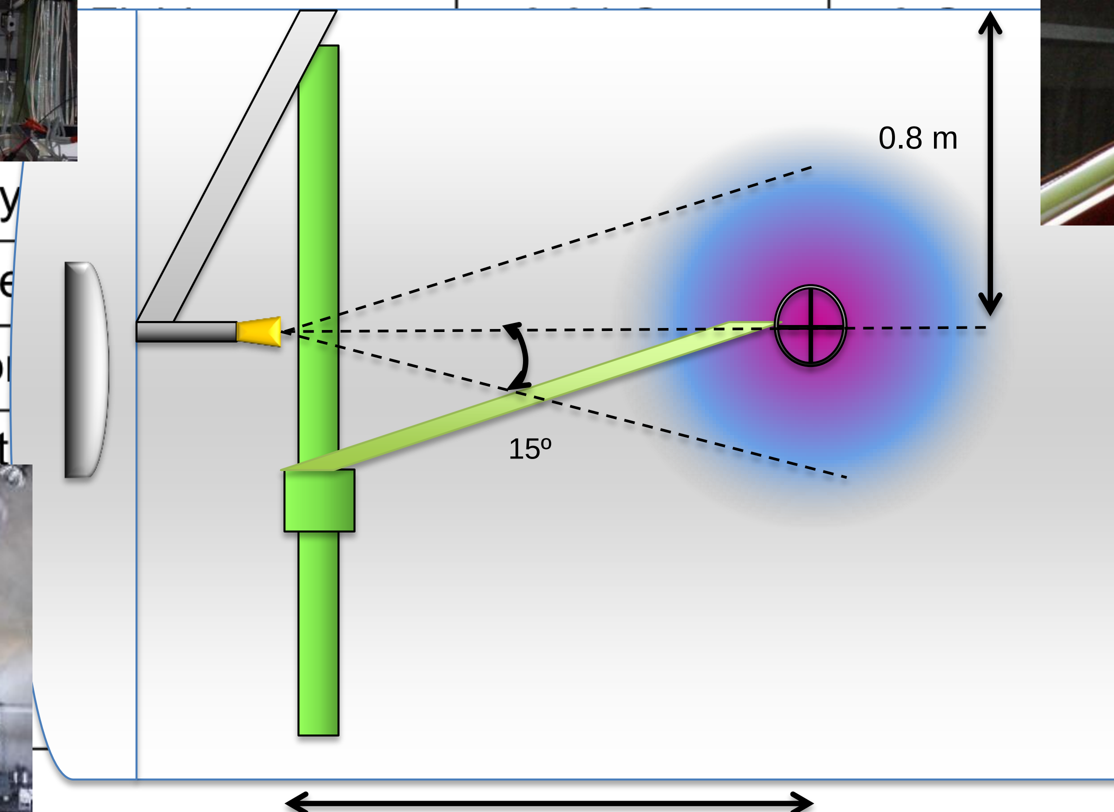
Phase I Experiment

Parameter	Mars Insertion	Experiment
Velocity	7000 m/s	700 m/s
I... ning Mass	44 amu	40 amu
...al Density	1e18 m^{-3}	3e18 m...
... Field	100 Gauss	300 Gau...
Dy...		
De...		
Io...		
St...		

MPD and Jet Injector



Dipole and RF Antenna



Thrust Stand

Magnetoshell

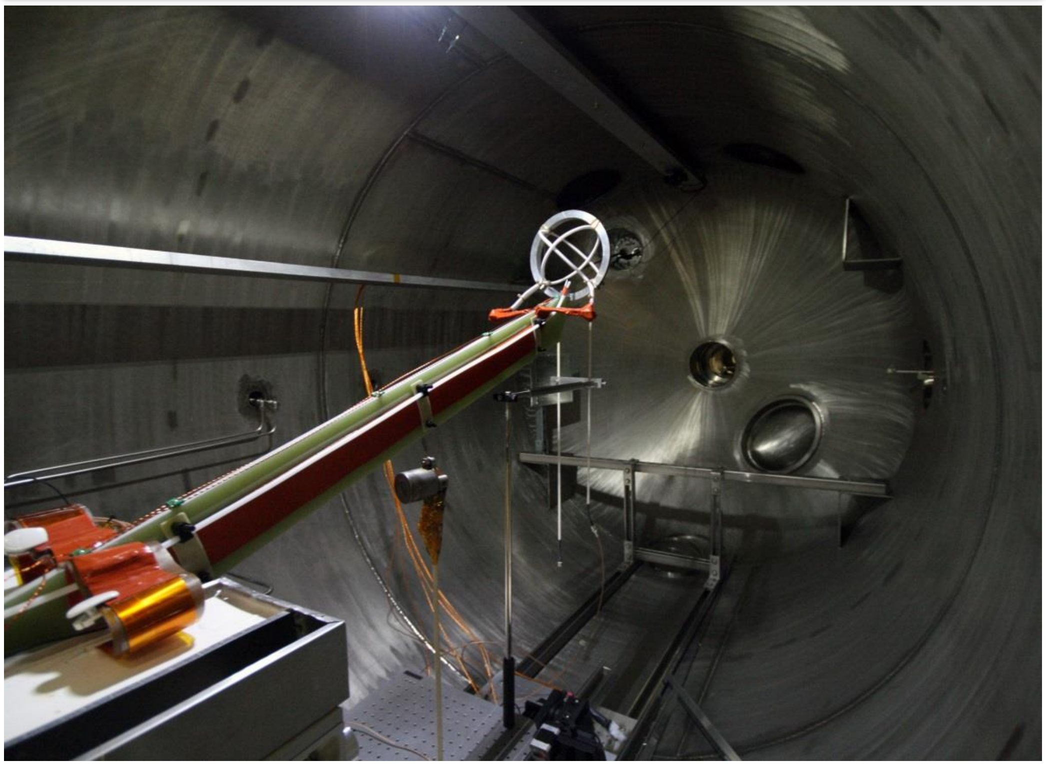
Experimental Setup

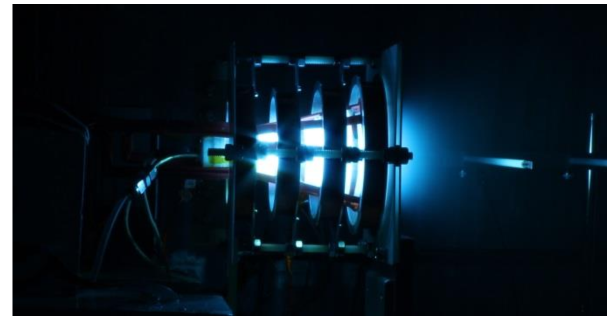
Dielectric Torsional Thrust Stand
- G-10 asymmetric swing-arm with 8.2 s period
- Optical displacement sensor
- Integrated power feed, diagnostic, thermal connections
- Cold gas, transient, and DC weight calibration

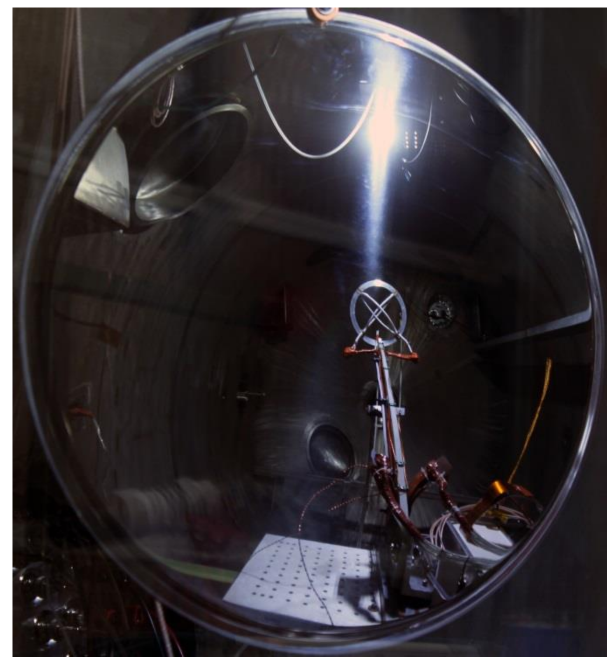
Downstream Probes
- Double Langmuir probe
- Magnetic Probe
- Fast-Ion Gauge

RF PPU – 1 kW AFRL thruster
- 150 kHz, 1.6 kV, and 4 Joules
- Decay time of 50 μs

Surface discharge PI
Internal gas feed (0-50 sccm)







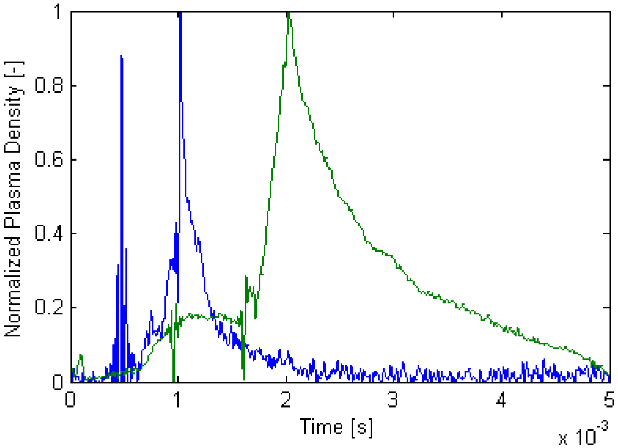
Magnetoshell installed in chamber. *Shown are two in-chamber power supplies (potted), low-inductance stripline, G-10 mount.*

MPD with Entrainment

Argon MPD

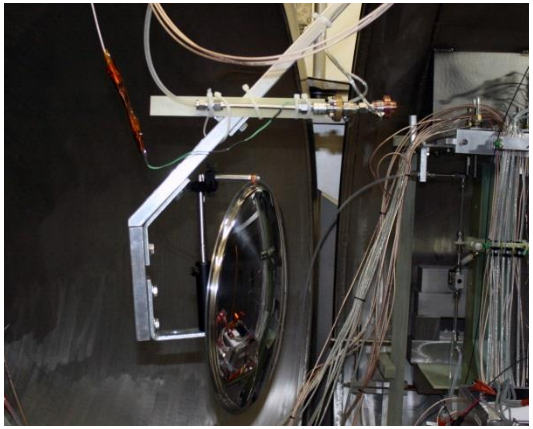
- Copper nozzle with thoriated tungsten cathode
- 2 km/s Argon plasma generated with 1 ms discharge
- Operated at 1.2 kV, 400 Amps , 8 kW discharge power
- Separate neutral gas injection prior to MPD iniation reduced jet speed to 800 m/s
- Plasma density 1-3 E 18 m^{-3}
- Neutral Jet density measured 0.5-2 E 18 m^{-3}

Pulsed MPD operating with an argon propellant and 2 ms discharge. *Shown is 90 psig, 1 ms argon puff at 400 Amp peak discharge.*



MPD downstream plasma density with and without a neutral pre-gas as blue and green, respectively.

Pulsed MPD operating with an argon propellant and 2 ms discharge.



MPD mounted in the MSNW vacuum facility. ***Shown is the MPD with integrated puff valve, spherical mirror, and in the background, the 'waterfall' power feed lines.***

Magnetoshells

Test Condition	Neutral Jet	MPD	Internal Flow	Dipole Field	RF
MPD	0 – 30 ms	1-5 ms	0 - 50 sccm	-	-
Jet	0 - 30 ms	-	-	-	-
Magnetoshell	-	-	0 - 50 sccm	0 - 500 Gauss	150 kHz, 1.0 -1.6 kV
Dipole Field and Jet	0 - 30 ms	1 ms	-	0 – 200 Gauss	-
Magnetoshell and Jet	10 - 30 ms	1-2 ms	0 - 50 sccm	0 – 200 Gauss	150 kHz, 1.6 kV

Fully Ionized Plasma Magnet

Magnetoshell operating with internal gas feed and intercepting only MPD plasma. *Shown is 50 sccm internal feed, 3 Joule RF, and 1 ms MPD discharge at 1.2 kV and 1 ms delay.*

Neutral Collision Dominated Magnetoshell

Magnetoshell operating with internal gas feed and intercepting an accelerated neutral and plasma jet. *Shown is 50 sccm internal feed, 3 Joule RF, and 1 ms MPD discharge at 1.2 kV following a 20 ms neutral puff.*

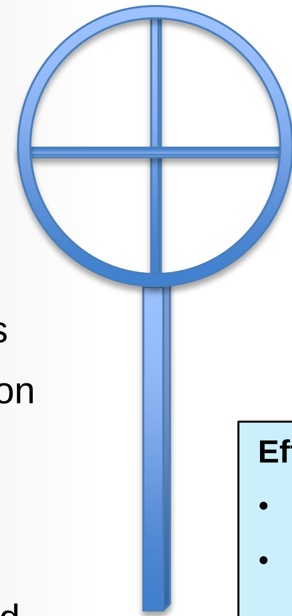
Thrust Stand Results

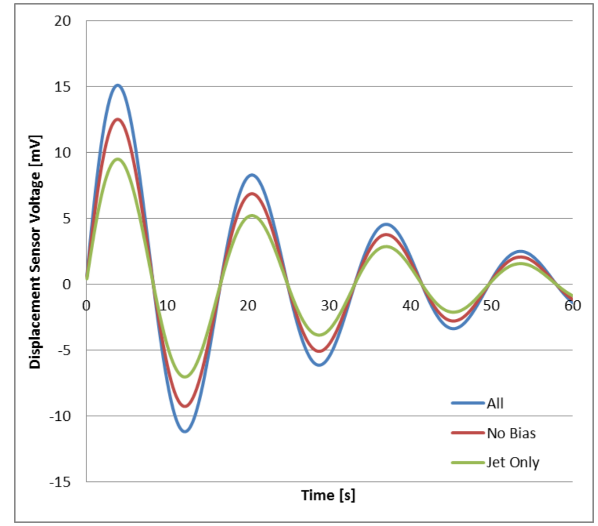
Impulse Measurements

- Impulse for only MPD and Neutral Gas
- Impulse for Bias Field and Jet
- Impulse for RF, Jet at Various Bias

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 magnetoshell area assumes circular, uniform cross section and 100% capture

Operating Condition	Measured Drag	Effective Area	Relative Drag
Magnetoshell, MPD with Neutral Flow, with Bias	220 mN	2.3 m^2	**1150**
Magnetoshell, MPD with Neutral Flow, no Bias	110 mN	1.1 m^2	550
MPD with Neutral Flow and Bias	190 μN	0.02 m^2	1

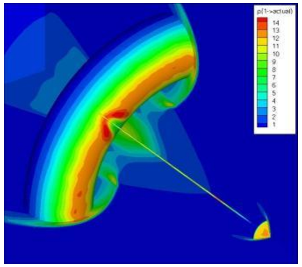
Error bars are significant for these measurements but do not change results (1000X increase in thrust)

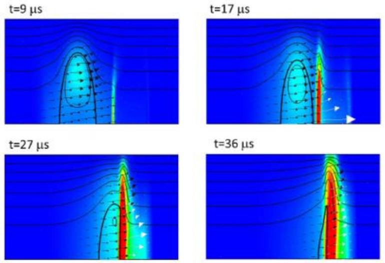
- Potential errors include thrust stand calibration (10%+), Coefficient of Drag (assumed 2), Average velocity, cross sections, and temporal distributions

Phase II

1. Mission and Reentry Analysis

- LaRC Aerocapture Experts
- ➢ Couple re-entry modeling with Magnetoshell plasma dynamics





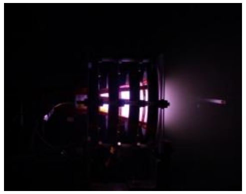
2. Full 3D Simulation at UW

- ➢ Leverage existing AFOSR/DOE neutral entrainment code

3. Combination Scaling Study and Space Hardware Development

- *Primary Questions: How do these scale? What about orbital velocities?*
- **Answer: Develop a smaller, low power Magnetoshell and fly it**

- ➢ Design and Demonstrate a 100 W, 3U capable Magnetoshell



Technology Development Plan

The primary challenge of this technology is the lack of ground facilities to test a full scale, full neutral velocity Magnetoshell

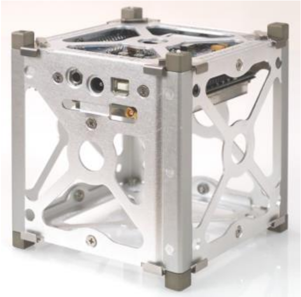
Phase I
Prove Concept
Mission Rationale

Phase II
Mission Integration
Prove Scaling and Models
Design Flight Hardware

Test
Sub-Orbital
Orbital Small-Sat

3U Demonstration Leading to Martian and Deep Space Orbiter Missions

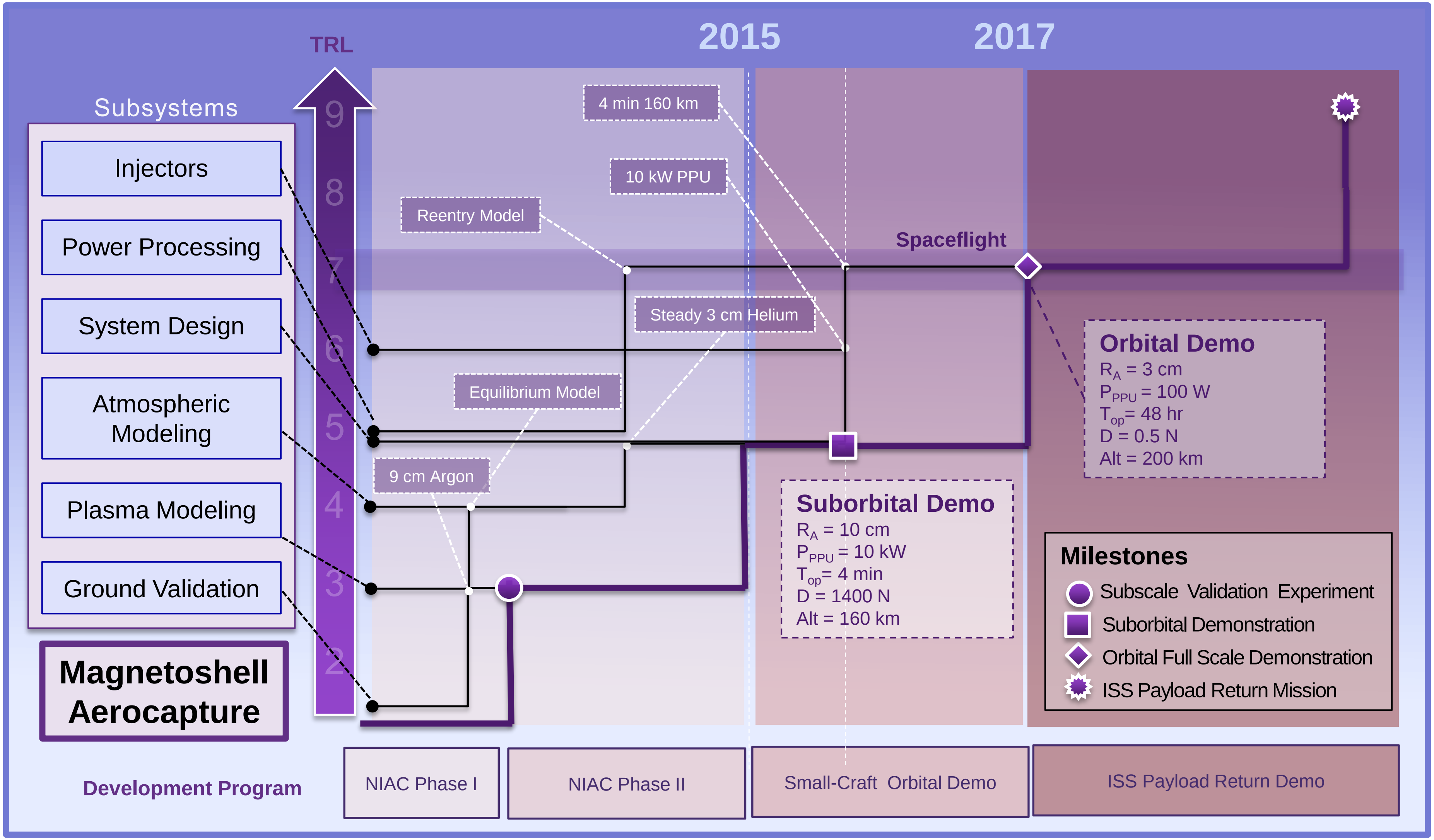
- Fly a Low Power Magnetoshell
- Sub-orbital attitude modification demo
- On-orbit nanosat LEO deorbit demo



Phase III will demonstrate an earth re-entry in a 3U P-POD or ESPA configuration. *A 1U PPU, 1U Magnetoshell, and 1U Core/Stabilizer/Com will be designed in Phase II. Shown are two off-the-shelf microsatellites by PUMKIN*

SpaceLoft XL. *Capable of 95-160 km altitudes. 4+ minutes of flight.*

Technology Roadmap for Magnetoshell Aerocapture



References and Publications

Publications:

- Kirtley, D. et al. “Plasma Magnetoshell Aerocapture Design and Scaling”. Journal of Spacecraft and Rockets, Pending (2013).
- SelenianBoondocks.com “Magnetoshell Braking”, Pending (2013).
- Next Big Future.com “Plasma magnetoshell aerobreaking should be one thousand times better than aerobraking”, Sept 2012.
- Scoop.it “Plasma magnetoshell aerobreaking should be one thousand times better than aerobraking” Sept 2012.
- Slough, J., Kirtley, D., Pancotti, A. “Plasma Magneto-Shell for Aerobraking and Aerocapture”. International Electric Propulsion Conference, IEPC-2011-303 (2011)

References:

- Lotz, Wolfgang. "Electron-impact ionization cross-sections and ionization rate coefficients for atoms and ions." *The Astrophysical Journal Supplement Series* 14 (1967): 207.
- Atmosphere, US Standard. "National Oceanic and Atmospheric Administration." *National Aeronautics and Space Administration, and United States Air Force, Washington, DC* (1976).
- Chen, Francis F., and M. A. Lieberman. Introduction to plasma physics and controlled fusion. Plenum Press, New York, 1984.
- Peter A, Gnoffo, et al. "Prediction and Validation of Mars Pathfinder Hypersonic Aerodynamic Data Base." (1998).
- Hall, Jeffery L. "A review of ballute technology for planetary aerocapture." *4th IAA Conference on Low Cost Planetary Missions, Laurel, MD*. 2000.
- Gnoffo, Peter A. "Computational aerothermodynamics in aeroassist applications." *AIAA paper* 2632 (2001): 2001.
- Gnoffo, Peter A., and Brian P. Anderson. "Computational analysis of towed ballute interactions." *AIAA paper* 2997.8 (2002).
- Losev, S. A., et al. Physical and chemical processes and gas dynamics: cross sections and rate constants. Progress in Astronautics and Aeronautics 196 (2002).
- Hall, Jeffery L., Muriel A. Noca, and Robert W. Bailey. "Cost-benefit analysis of the aerocapture mission set." *AIAA Paper* 4958 (2003).
- Smirnov, Boris M. Physics of atoms and ions. Springer, 2003.
- Lyons, Daniel T., and Wyatt Johnson. "Ballute aerocapture trajectories at Neptune." (2004).
- Rohrschneider, Reuben R., and Robert D. Braun. "A Survey of Ballute Technology for Aerocapture." (2005).
- Beinstock, B. atikinson, D. “NEPtune Orbiter with Probes”, Outer Planets Assessment Group (2005).
- Lockwood, Mary Kae. "Titan aerocapture systems analysis." *Aerocapture Systems Analysis for a Titan Mission, NASA/TM-2006-214273* (2006)
- Munk, M., and Spilker, T. “Aerocapture Mission Concepts for Venus, Titan and Neptune” International Planetary Probe Workshop (2008).