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

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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 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 known 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.
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

<table>
<thead>
<tr>
<th>Mission</th>
<th>Mars Manned</th>
<th>Venus Sample Return</th>
<th>Neptune Orbiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming Velocity</td>
<td>5.5 km/s</td>
<td>10.6 km/s</td>
<td>26.7 km/s</td>
</tr>
<tr>
<td>Neutral Molecular Weight</td>
<td>43.4 amu</td>
<td>43.4 amu</td>
<td>2.5 amu</td>
</tr>
<tr>
<td>Ion Average Weight</td>
<td>15.0 amu</td>
<td>14.6 amu</td>
<td>1.6 amu</td>
</tr>
<tr>
<td>Directed Neutral Energy</td>
<td>7.0 eV</td>
<td>25.5 eV</td>
<td>9.4 eV</td>
</tr>
<tr>
<td>Aerocapture Max Density</td>
<td>1.3E19 #/m³</td>
<td>3E18 #/m³</td>
<td>3.5E18 #/m³</td>
</tr>
<tr>
<td>Entrance Altitude</td>
<td>200 km</td>
<td>300 km</td>
<td>2000 km</td>
</tr>
</tbody>
</table>
# The Benefits of Light, Reliable Magnetoshells for Aerocapture

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

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

<table>
<thead>
<tr>
<th>Time (Days)</th>
<th>Earth $\Delta V$ (km/s)</th>
<th>Mars $\Delta V$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>20.9</td>
<td>24.5</td>
</tr>
<tr>
<td>60</td>
<td>9.1</td>
<td>43.8</td>
</tr>
<tr>
<td>90</td>
<td>5.4</td>
<td>9.3</td>
</tr>
<tr>
<td>120</td>
<td>3.8</td>
<td>6.5</td>
</tr>
<tr>
<td>150</td>
<td>3.1</td>
<td>4.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (Days)</th>
<th>Earth $\Delta V$ (km/s)</th>
<th>Jupiter $\Delta V$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>65.5</td>
<td>83.5</td>
</tr>
<tr>
<td>250</td>
<td>20.9</td>
<td>32.8</td>
</tr>
<tr>
<td>500</td>
<td>10.6</td>
<td>13.6</td>
</tr>
<tr>
<td>750</td>
<td>8.9</td>
<td>7.3</td>
</tr>
<tr>
<td>1000</td>
<td>9.1</td>
<td>5.6</td>
</tr>
</tbody>
</table>
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

\[
\begin{align*}
n_{i,e,0}(r, t) \\
T_{i,e}(r, t) \\
\sigma_{ion, CEX, \text{ex}}(r, t) \\
D_\perp(r, t)
\end{align*}
\]

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

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

\[
\lambda_{CE} = \frac{1}{n_{n0} \sigma_{CE}} \quad r_i = \frac{mU_0}{eB}
\]

\[
\pi r_i < \lambda_{CE} \leq L_0
\]

- Ion gyroradius \((r_i)\) and charge exchange mean free path \((\lambda_{CE})\) are less than characteristic length
- Particle must stay confined for at least 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 $\sim$100 ms.

\[
\begin{align*}
\nu_{s-s} &= \frac{2n_s \sigma_T \ln \Lambda}{\pi^{1/2}} \left( \frac{m_e}{m_i} \right) \left( \frac{k_B T_e}{m_e} \right)^{-3/2} \quad [1/s] \\
T_{ion} &= \sigma_{ion}(T_e) n_i n_e \frac{V_o}{L_o} \Delta t \\
D_{Bohm} &\propto \frac{k_B T}{B} \\
D_\perp &\propto \eta_\perp \frac{k_B T}{B^2} \propto \frac{m_i k_B T^{1/2}}{B^2}
\end{align*}
\]

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

Ion and Electron Equilibration times are $\sim$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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mars Insertion</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>7000 m/s</td>
<td>700 m/s</td>
</tr>
<tr>
<td>Charging Mass</td>
<td>44 amu</td>
<td>40 amu</td>
</tr>
<tr>
<td>Initial Density</td>
<td>1e18 m⁻³</td>
<td>3e18 m⁻³</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>100 Gauss</td>
<td>300 Gauss</td>
</tr>
</tbody>
</table>

- 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.*
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 initiation reduced jet speed to 800 m/s
- Plasma density $1 \times 10^{18} \text{ m}^{-3}$
- Neutral Jet density measured $0.5 \times 10^{18} \text{ m}^{-3}$

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.

*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

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Neutral Jet</th>
<th>MPD</th>
<th>Internal Flow</th>
<th>Dipole Field</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPD</td>
<td>0 – 30 ms</td>
<td>1-5 ms</td>
<td>0 - 50 sccm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jet</td>
<td>0 - 30 ms</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnetoshell</td>
<td>-</td>
<td>-</td>
<td>0 - 50 sccm</td>
<td>0 - 500 Gauss</td>
<td>150 kHz, 1.0 -1.6 kV</td>
</tr>
<tr>
<td>Dipole Field and Jet</td>
<td>0 - 30 ms</td>
<td>1 ms</td>
<td>-</td>
<td>0 – 200 Gauss</td>
<td>-</td>
</tr>
<tr>
<td>Magnetoshell and Jet</td>
<td>10 - 30 ms</td>
<td>1-2 ms</td>
<td>0 - 50 sccm</td>
<td>0 – 200 Gauss</td>
<td>150 kHz, 1.6 kV</td>
</tr>
</tbody>
</table>

Fully Ionized Plasma Magnet

Neutral Collision Dominated Magnetoshell

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.

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 cm²
- Effective magnetoshell area assumes circular, uniform cross section and 100% capture

## Operating Condition Results

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Measured Drag</th>
<th>Effective Area</th>
<th>Relative Drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetoshell, MPD with Neutral Flow, with Bias</td>
<td>220 mN</td>
<td>2.3 m²</td>
<td>1150</td>
</tr>
<tr>
<td>Magnetoshell, MPD with Neutral Flow, no Bias</td>
<td>110 mN</td>
<td>1.1 m²</td>
<td>550</td>
</tr>
<tr>
<td>MPD with Neutral Flow and Bias</td>
<td>190 µN</td>
<td>0.02 m²</td>
<td>1</td>
</tr>
</tbody>
</table>

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

Development Program
- NIAC Phase I
- NIAC Phase II
- Small-Craft Orbital Demo
- ISS Payload Return Demo

Milestones
- Subscale Validation Experiment
- Suborbital Demonstration
- Orbital Full Scale Demonstration
- ISS Payload Return Mission

Magnetoshell Aerocapture
- Injectors
- Power Processing
- System Design
- Atmospheric Modeling
- Plasma Modeling
- Ground Validation

Subsystems

Reentry Model
- 10 kW PPU
- 4 min 160 km

Equilibrium Model
- Steady 3 cm Helium

Steady 3 cm Helium
- 9 cm Argon

Orbital Demo
- $R_A = 3$ cm
- $P_{PPU} = 100$ W
- $T_{op} = 48$ hr
- $D = 0.5$ N
- Alt = 200 km

Suborbital Demo
- $R_A = 10$ cm
- $P_{PPU} = 10$ kW
- $T_{op} = 4$ min
- $D = 1400$ N
- Alt = 160 km

NIAC Phase I
NIAC Phase II
Small-Craft Orbital Demo
ISS Payload Return Demo
Publications:

- 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.

References: