Impact of Magnetohydrodynamic (MHD) Induced Drag on High Ballistic Coefficient Aerocapture at Neptune

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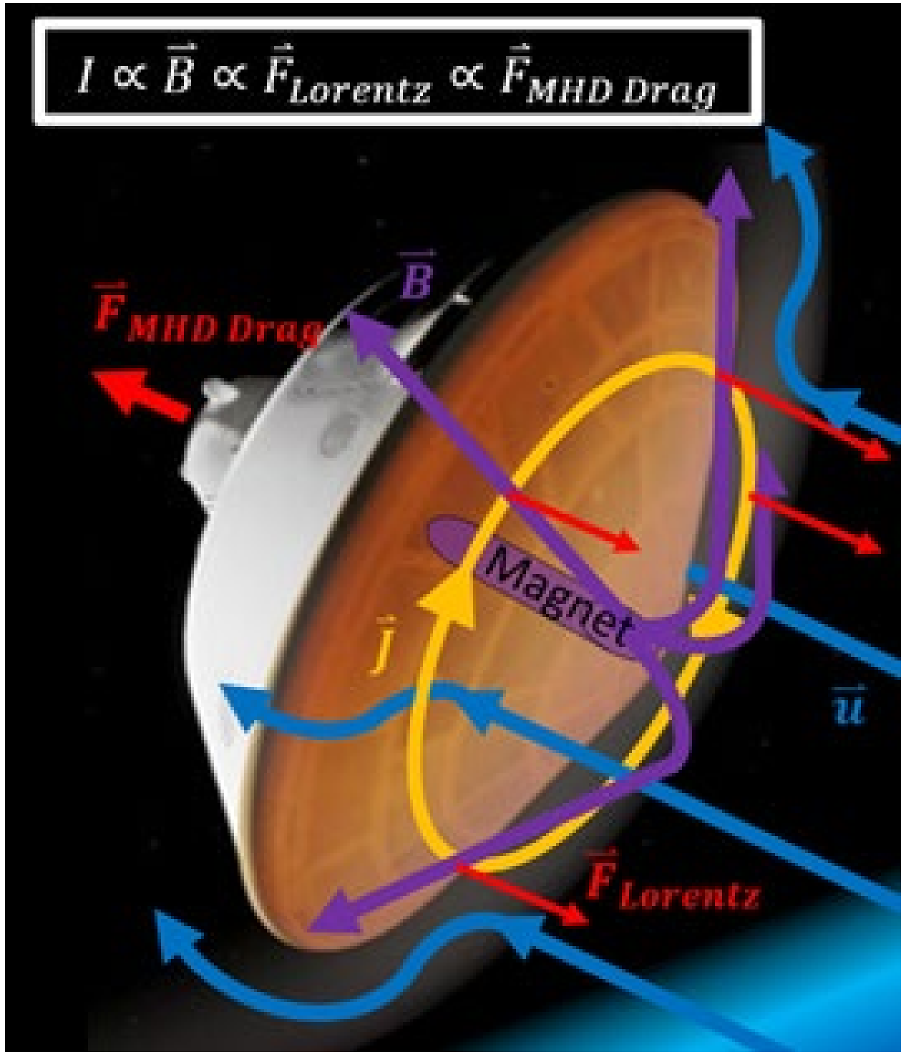
Magnetohydrodynamic (MHD) Drag Force Control for Aeroassist Applications

- What is it?
  - Hypersonic entry produces an ionized plasma surrounding the spacecraft
  - With an onboard magnet, a magnetic field, $\vec{B}$, can be applied on the plasma create an electron current, $\vec{J}$, and induce a Lorentz force:

$$\vec{\boldsymbol{F}}_{\boldsymbol{Lorentz}} = \vec{\boldsymbol{J}} \times \vec{\boldsymbol{B}}$$

  - **This force is in addition to aerodynamic forces**
  - Assuming a uniform magnetic field, the Lorentz forces will sum and act equally and oppositely on the vehicle in only the drag direction
  - The current, I, to an electromagnet configuration can be manipulated to allow for active control
- Potential Advantages
  - Higher atmospheric activation & increased deceleration forces → Enables faster hyperbolic inertial entry velocities → **Decreased interplanetary transit times**
  - Lower the aerodynamic heating → **Decreased requirements on the Thermal Protection System (TPS)**
  - Increase the useful mission timeline → **Improved vehicle controllability**
  - Decelerate more mass → **Increased scientific payload capacity**
  - Does not require mass ballasts, aerodynamic flaps, jettisons, or a complex size-changing aeroshell

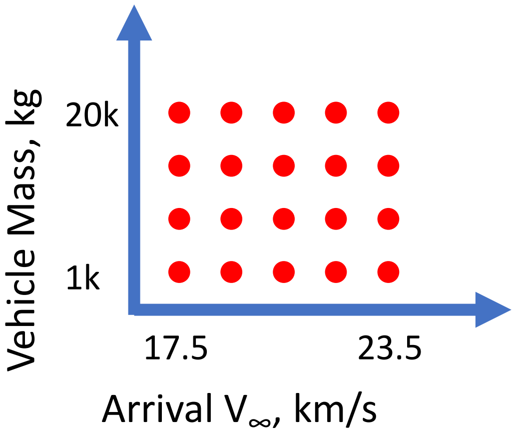


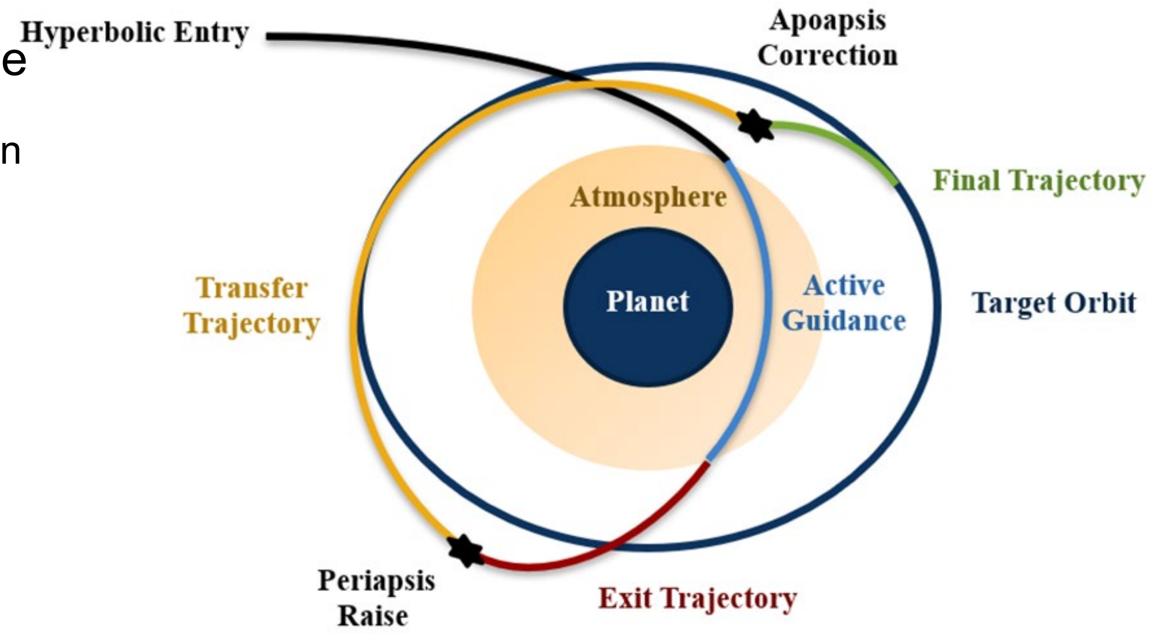
Background and Study Hypothesis

- Effort funded through a FY24 NASA Langley Center Innovation Fund (CIF) Internal Research and Design (IRAD) project
  - "Vehicle Design and Performance Simulation Capabilities Development for Magnetohydrodynamic Aerocapture" – Dr. Justin Green (Principal Investigator)
    - Objective: perform and document design trades for MHD equipped entry vehicle that factor in the cross-coupling impacts from multiple disciplines.
- Preliminary analysis covering a limited range of cases indicated the benefits for MHD (relative to a vehicle utilizing aerodynamic-only control) may increase as vehicle ballistic coefficient and entry velocities increase
- Objective of current effort is to validate this hypothesis by performing a structured analysis covering a wide range of entry masses and hyperbolic arrival velocities
  - Entry mass surrogate for ballistic coefficient
  - Hyperbolic arrival velocity (V_{∞}) surrogate for inertial entry velocity

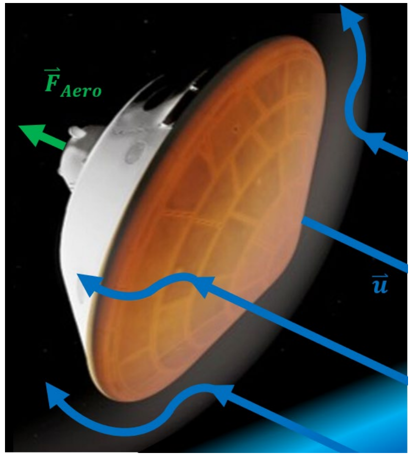
Approach: Neptune Aerocapture Case Study

- Aerocapture targeting a 430,000 km x 3,986 km Neptune orbit with Triton flybys
  - Aerocapture is the use of a planet’s atmosphere to slow down and transfer into an orbit around the planet
  - Aerocapture reduces the ∆V required to reach a target orbit, which allows for less propellant and thus less mass
- 3 degree-of-freedom (DoF)
- 70º sphere cone Mars Science Laboratory (MSL) class vehicle
- Comparing following implementations:
  - Aerodynamic only: Bank Angle Modulated (BAM)
  - MHD enabled: MHD Drag Modulated
- Currently assume MHD and aerodynamic forces are independent and cumulative
- Explored range of entry masses from 1 t to 20 t and range of hyperbolic arrival velocities from 17.5 km/s to 23.5 km/s
- Perform TPS sizing comparison for select cases

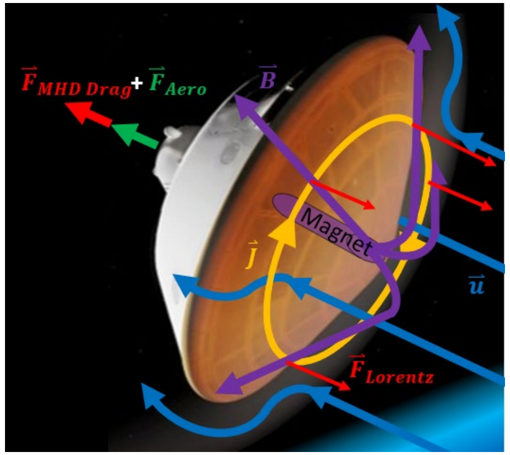




Aerodynamic Only

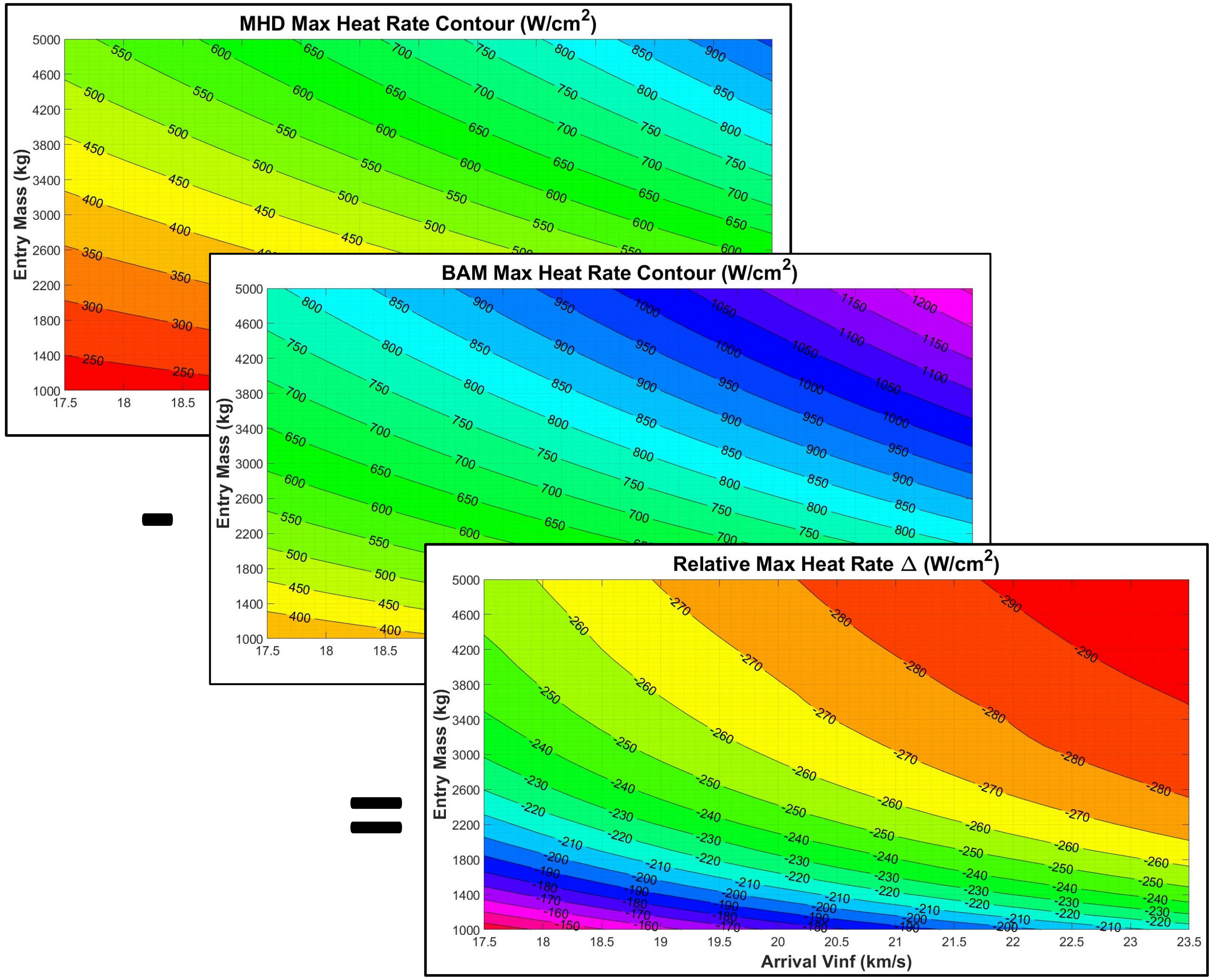


MHD Enabled

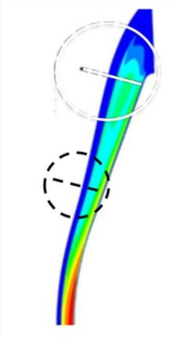
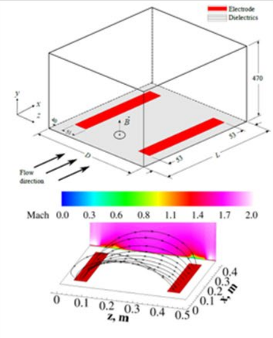
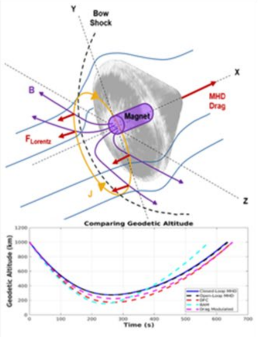
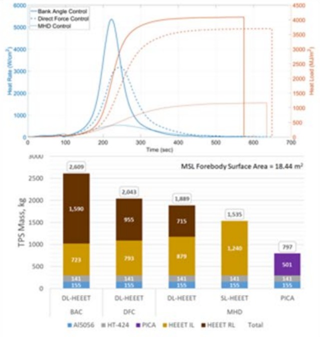


Approach: Two-Tiered Technical Analysis

- Relative Flight Performance Assessment

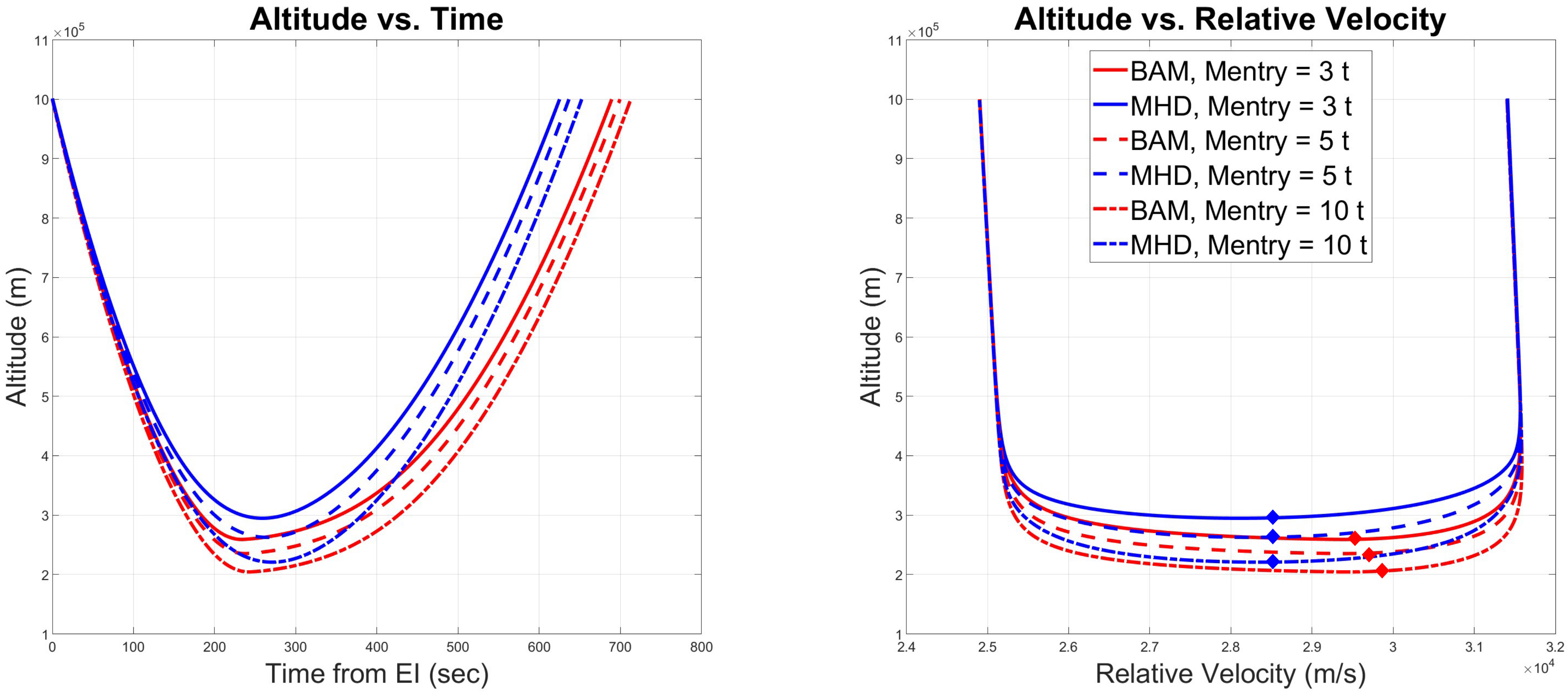


- Aeroheating and TPS Sizing Analyses
  - Multidisciplinary assessment of select options comparing relative mass impacts due to TPS and MHD systems as a function of entry mass and entry velocity

LAURA	CFDWARP	POST2	FIAT
			
Conduct aero-heating analysis to select places of ionization and flow velocity for MHD system analysis	Port LAURA results into CFDWARP to calculate electrical and thermal conductivities of ionized flow for sizing MHD patch system and calculating Lorentz forces needed for controls analysis	Port results from LAURA and CFDWARP into POST2 for calculating entry trajectories and comparing MHD control results with other aerodynamic control strategies	Utilize trajectory information from POST2 to calculate heat rates and heat loads on the spacecraft and size the Thermal Protection System based on known properties of materials such as HEEET and PICA

Results: Relative Flight Performance Assessment
Flight Profile of BAM vs. MHD over range of Entry Masses

MSL Neptune Aerocapture at Arrival Vinf = 17.5 km/s



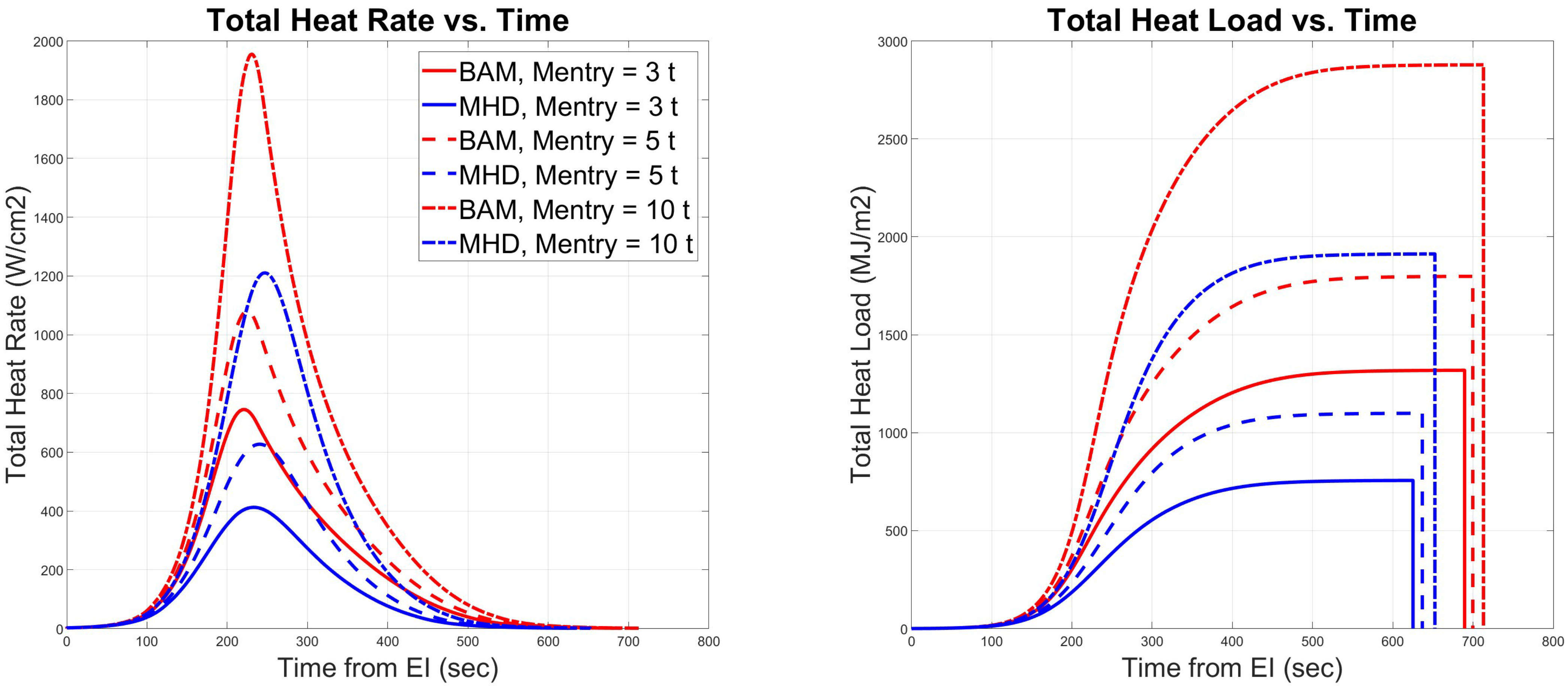
Altitude vs. Time

Altitude vs. Relative Velocity

MHD decelerates faster and has lower velocity at periapsis (and peak heating)

Results: Relative Flight Performance Assessment
Aeroheating of BAM vs. MHD over range of Entry Masses

MSL Neptune Aerocapture at Arrival Vinf = 17.5 km/s - Stagnation Point Heating

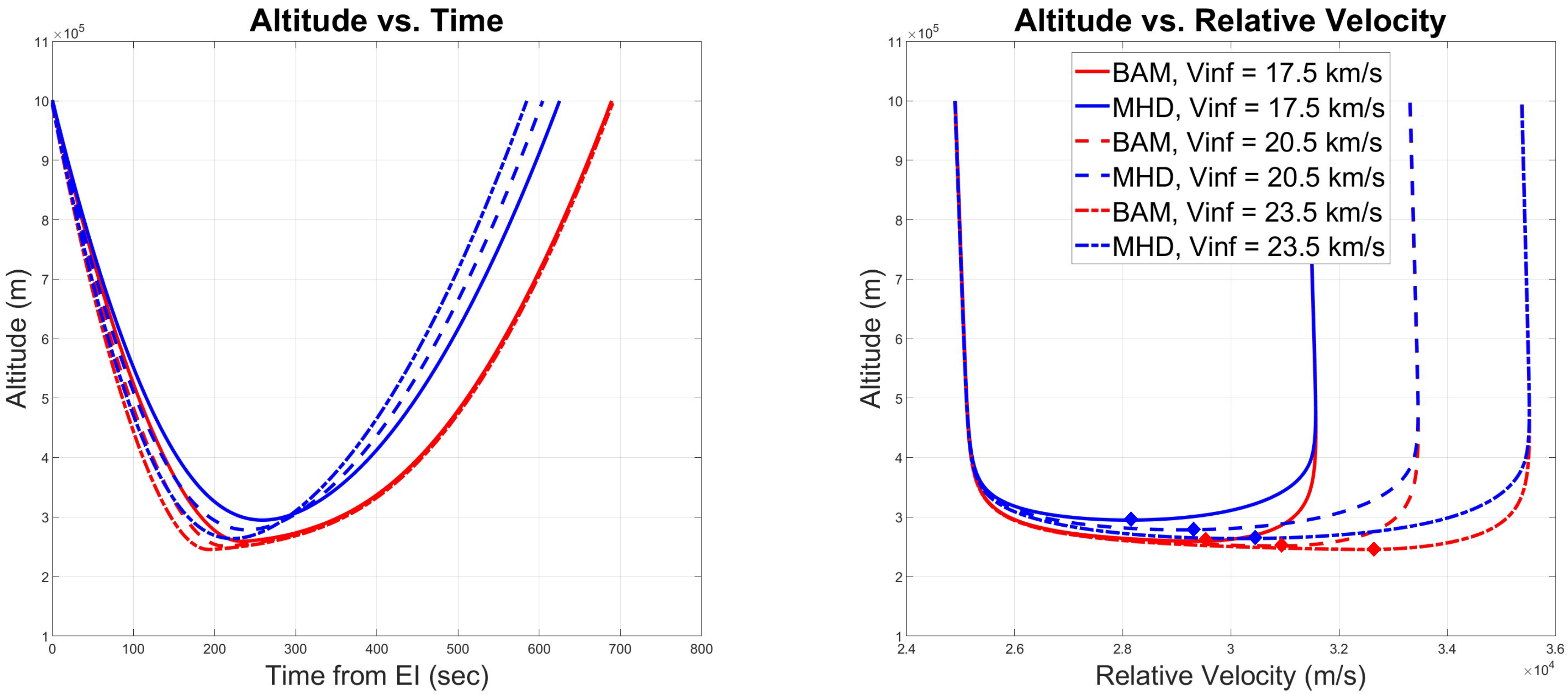

Total Heat Rate vs. Time

Total Heat Load vs. Time

Benefit for MHD heat rates and loads (relative to BAM) increases as entry mass increases

Results: Relative Flight Performance Assessment
Flight Profile of BAM vs. MHD over range of Arrival Velocities

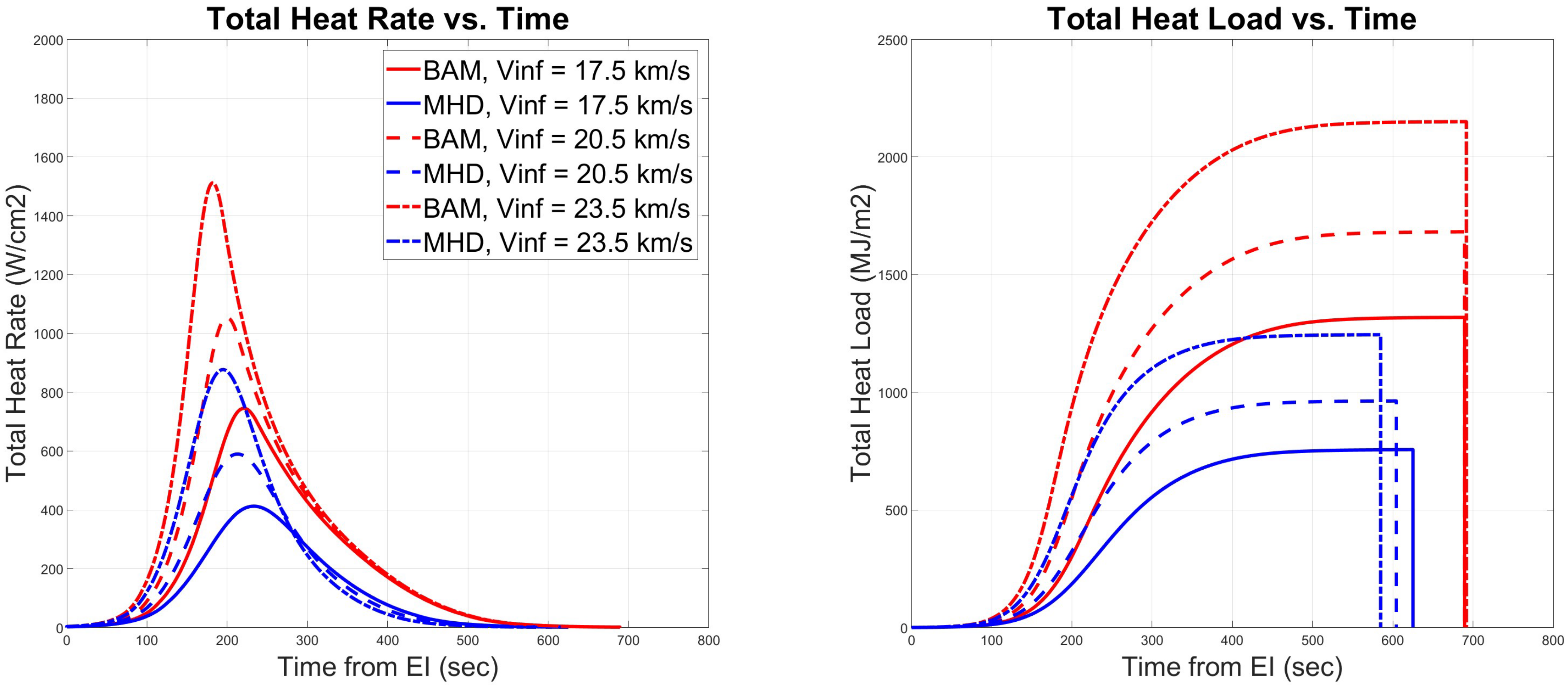
MSL Neptune Aerocapture with Entry Mass = 3 t



MHD decelerates faster and has lower velocity at periapsis (and peak heating)

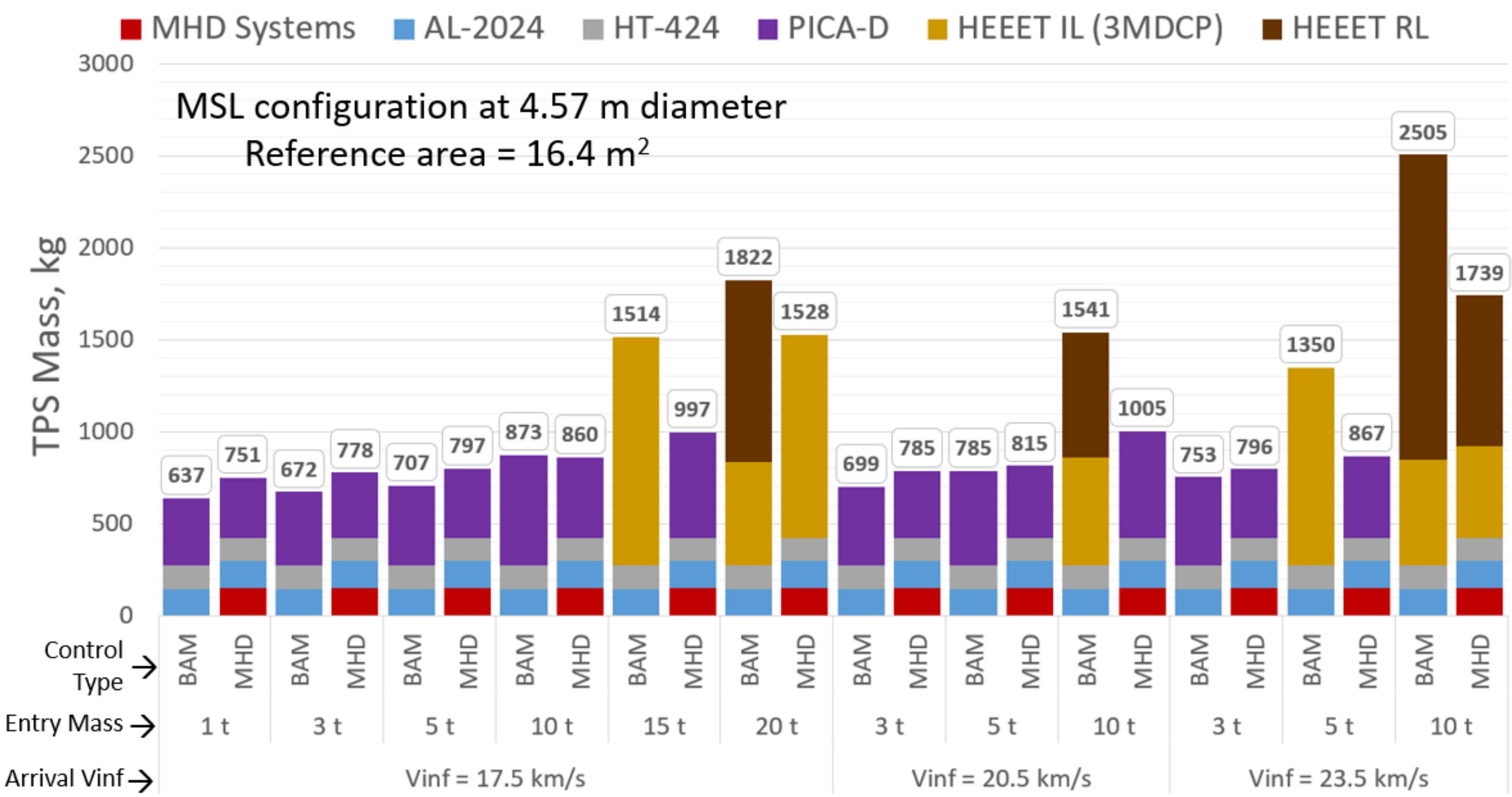
Results: Relative Flight Performance Assessment
Aeroheating of BAM vs. MHD over range of Arrival Velocities

MSL Neptune Aerocapture with Entry Mass = 3 t - Stagnation Point Heating



Benefit for MHD heat rates and loads (relative to BAM) increases as entry velocity increases

Results: TPS and Electromagnet Sizing



- Electromagnet Sizing
  - 10 electromagnets concentrically positioned around forebody circumference
  - Total power consumed: 5.5 kW
  - Total magnetic field: 1.06 T
  - Total mass w/ core: 167 kg
- TPS Sizing
  - PICA-D considered for peak heat rates < 2500 W/cm^2
  - Single layer HEEET (aka 3D mid-density carbon phenolic or 3MDCP) considered for peak heat rates between 2500-3500 W/cm^2
  - Dual layer HEEET considered only for peak heat rates > 3500 W/cm^2

Mass benefit for MHD relative to BAM increases with entry mass and arrival velocity

Key Findings and Conclusions:

- MHD drag augmentation reduces the amount of TPS mass relative to aerodynamic only (BAM)
  - At low entry mass and velocity, the MHD system mass penalty offsets the TPS mass reduction
  - As entry mass and velocity increase, the TPS mass savings begins to outweigh the mass penalty of the MHD system, with the overall benefit increasing as entry mass and velocity are further increased
- MHD drag augmentation potentially good application for mid-L/D configurations delivering large cargo to planetary orbit (via aerocapture) or planetary surfaces (via entry, descent and landing)
- Anticipate favorable results for MHD lift modulation and direct force control strategies, but future investigation is needed
- Impact of MHD drag (or lift) augmentation on interplanetary transit time requires future investigation