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Models for Supersonic DGB Parachutes in the Wake of a Slender Body

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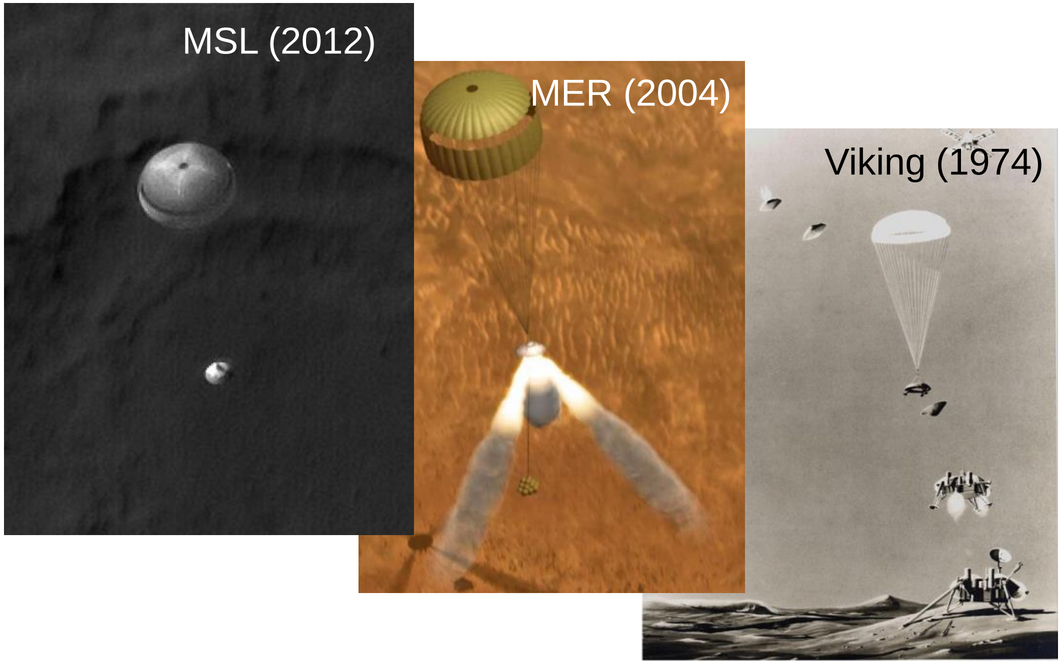
Disk-Gap-Band (DGB) Parachute Heritage



- Developed in the 60s & 70s for Viking
  - High Altitude Testing
  - Wind Tunnel Testing
  - Low Altitude Drop
- Successfully used on 5 Mars missions
  - Leveraged Viking development

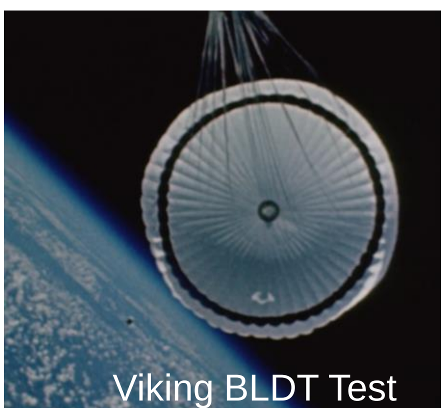
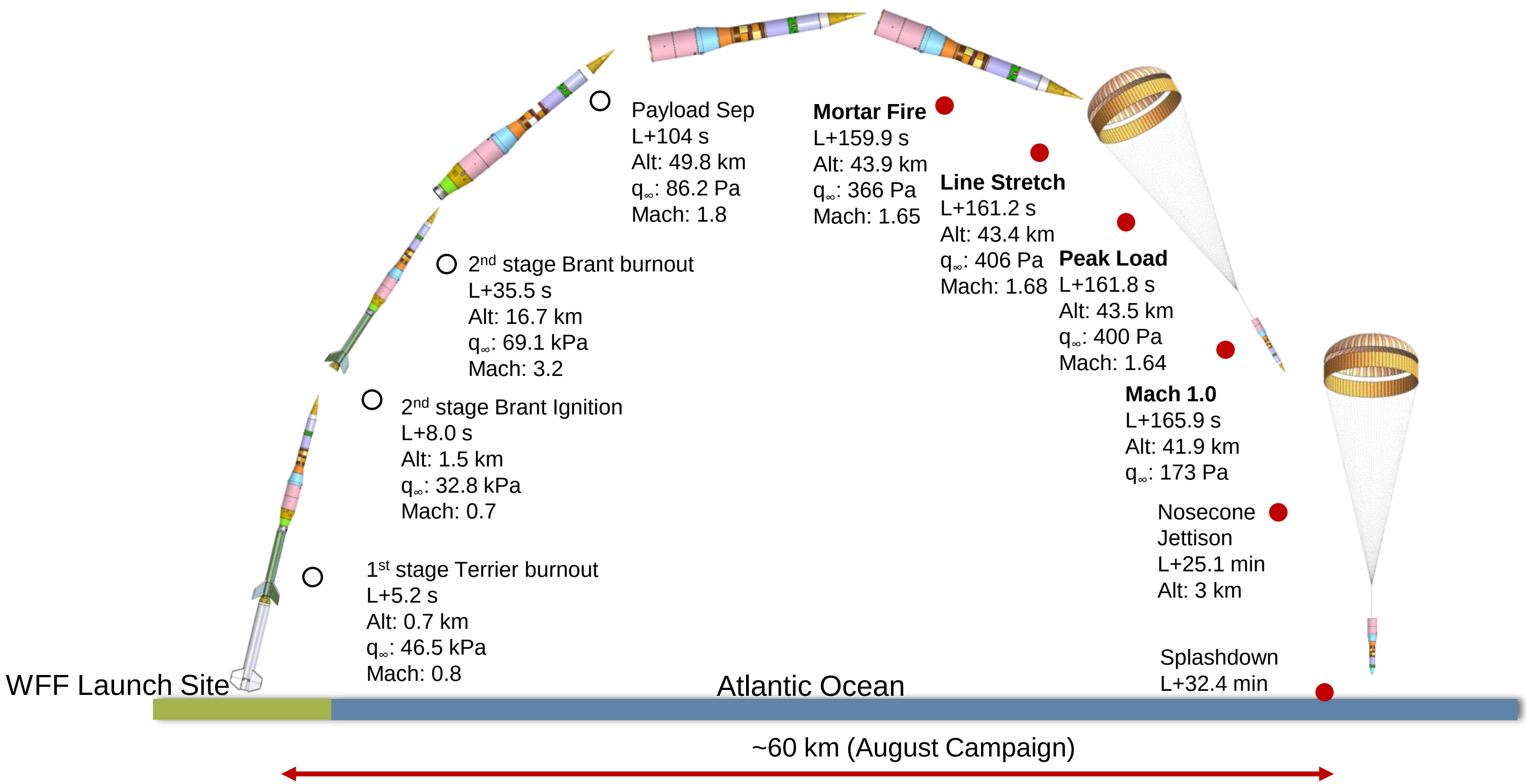


Image credit: mars.nasa.gov

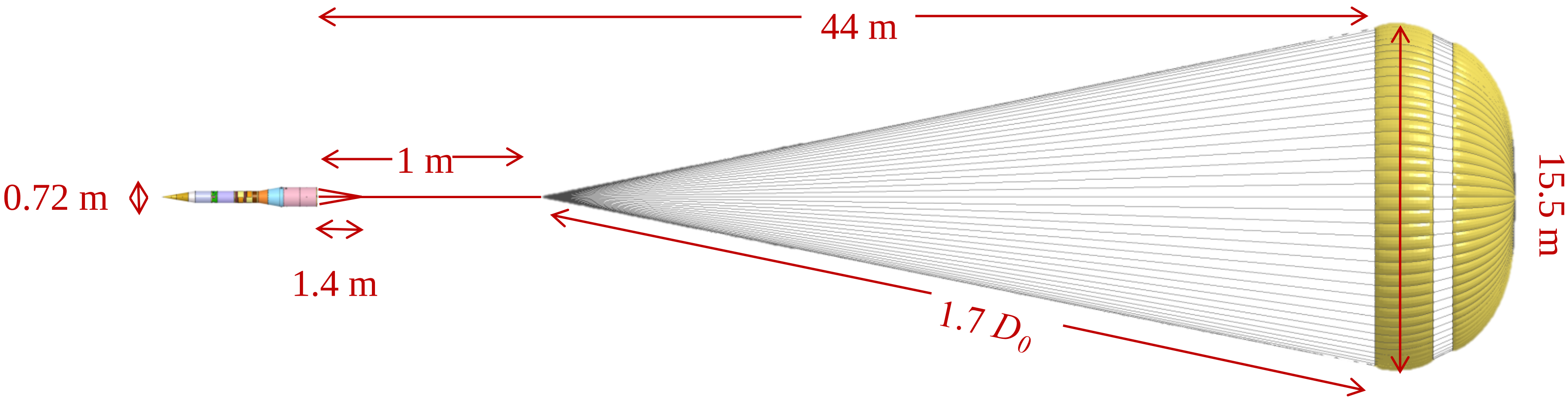
The ASPIRE Project

- The **A**dvanced **S**upersonic **P**arachute **I**nflation **R**esearch **E**xperiments Project was established to study the deployment, inflation and performance of DGBs in supersonic, low-density conditions
- DGBs to be tested in a series of sounding rocket flights out of Wallops Flight Facility (WFF) starting summer 2017



ASPIRE Parachute & Modeling Challenges

- D_0 = 21.5 m DGB configuration: similar to MSL & Mars 2020 (planned)



- Parachute system models are necessary to:
  - Predict opening parachute loads
  - Evaluate vehicle trajectory for targeting, range safety, recovery
  - Evaluate loads & accelerations imposed by the parachute on payload
  - Guide sensor selection & placement
  - Examine differences between parachutes tested in slender body wakes (test) and blunt body wakes (at Mars flight)
- Majority of past supersonic DGB tests have been in blunt body wakes
  - **Only four successful supersonic slender body tests**
  - **All featured short suspension lines (1.0 x D_0)**

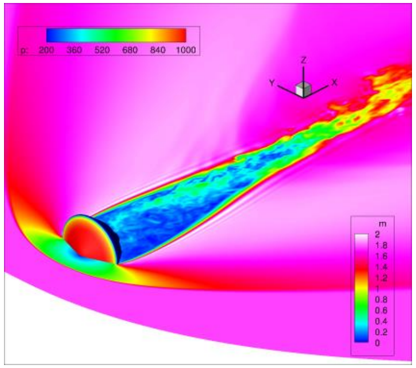
Modeling Approach

- Used the MSL DGB model, which successfully predicted at Mars performance, as a baseline (Cruz *et al,* AIAA 2013-1276)
- Leveraged results from historical supersonic flight test, wind tunnel tests & Mars entries
  - Eight flight tests: four blunt bodies, four slender bodies
  - Reconstructed performance at Mars: Phoenix, MSL
  - Wind tunnel test data from ten separate campaigns
- CFD simulations of the wakes behind blunt and slender bodies
  - Parallel unstructured implicit Navier-Stokes solver (US3D) w/ Detached Eddy Simulations (DES) & low dissipation fluxes
  - Flow conditions match ASPIRE deployment:

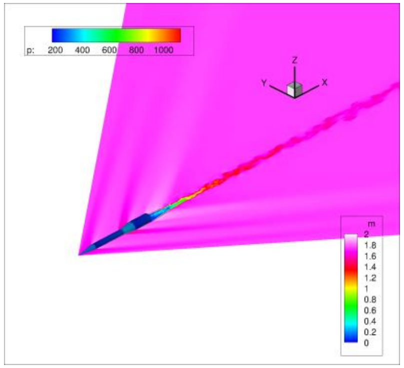
Atmosphere	Altitude	Mach Number	Dynamic Pressure
Dry air	41 km above sea level	1.75	538 Pa

  - Simulations conducted both with & without canopy in wake
  - Examined time-averaged & fluctuating properties at the location of the parachute

MSL geometry:

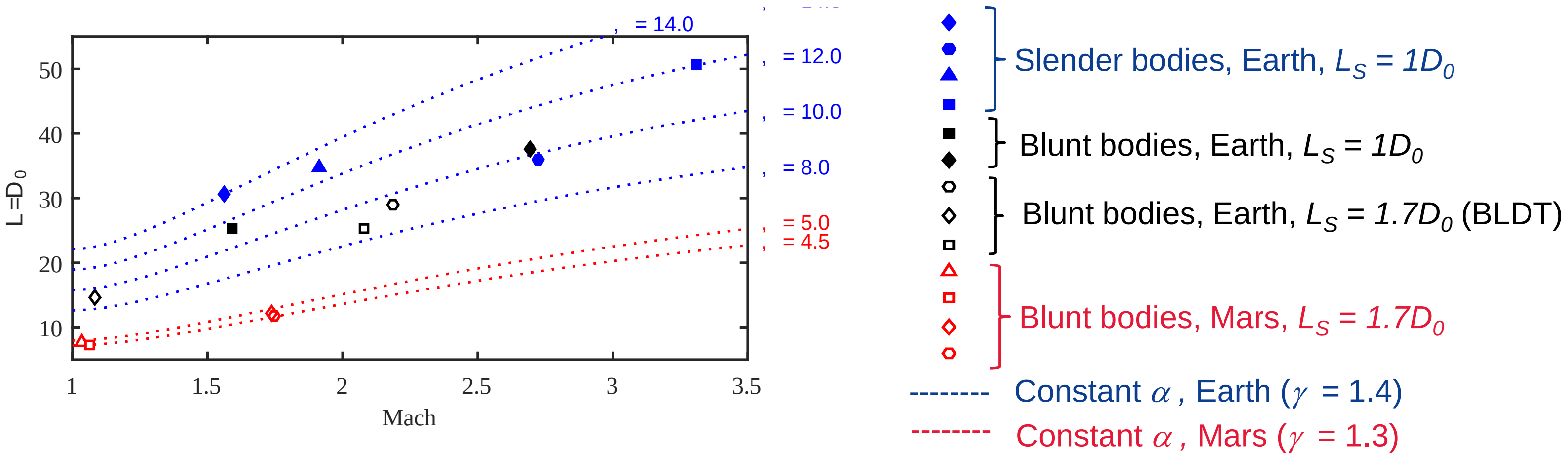


ASPIRE geometry:



Supersonic Inflation

- Past supersonic DGB inflations characterized by *inflation distance (L)*
  - Distance traveled by the payload during inflation
  - Related to the volume of gas (air, CO_2) that is ingested by the parachute



- The inflation distance depends on: $\dfrac{L}{D_0} = \alpha \left(\dfrac{\rho_c}{\rho_\infty} \right)$
  - The size of the parachute (D_0)
  - The density of the inflation gas (behind the bow shock – atmosphere dependent)
  - α is a canopy-specific parameter accounting for: volume, effective inlet area, etc
- Previous inflations at Mars fall between $4.5 < \alpha < 5.2$
- For inflations at Earth:
  - BLDT inflations: $8 < \alpha < 10$
  - **Slender body inflations were slower in general, but may be influenced by L_S (constrained inlet area) or canopy loading (*mg/C_DS_0* -- departure from infinite mass)**

ASPIRE Inflation Model

- During inflation the force exerted by the parachute is given by:

$$F_P(t) = q_\infty C_D S_0 C_X \left(\frac{t}{t_{inf}}\right)^4$$

  - C_X = 1.407 is the opening load factor
  - t_{inf} is the inflation time
  - $q_\infty C_D S_0$ is the steady state drag of the parachute at deployment Mach

Identical to MSL model

- Inflation time t_{inf} is determined from the inflation distance:

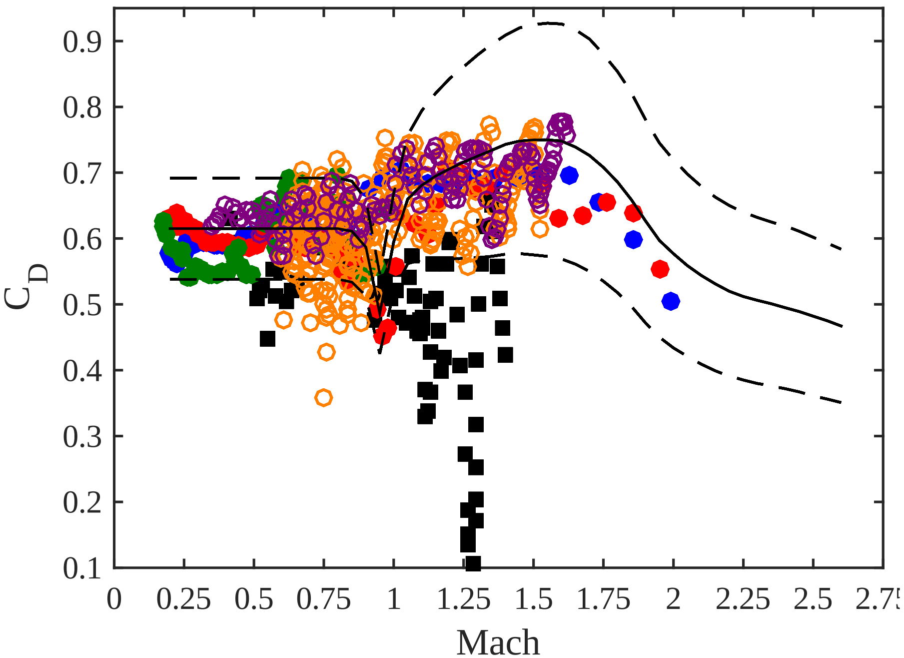
$$L = \alpha \left(\frac{\rho_c}{\rho_\infty}\right) D_0$$

  - Assume $5 \leq \alpha \leq 9$
  - Time to travel L (ie t_{inf}) is dependent on the force exerted by parachute, which is in turn dependent on t_{inf}
  - Initially assume $t_{inf} = D_0/V_{inf}$ w/inflation velocity V_{inf} = 30 m/s (MSL)
  - Iterative process to determine t_{inf}

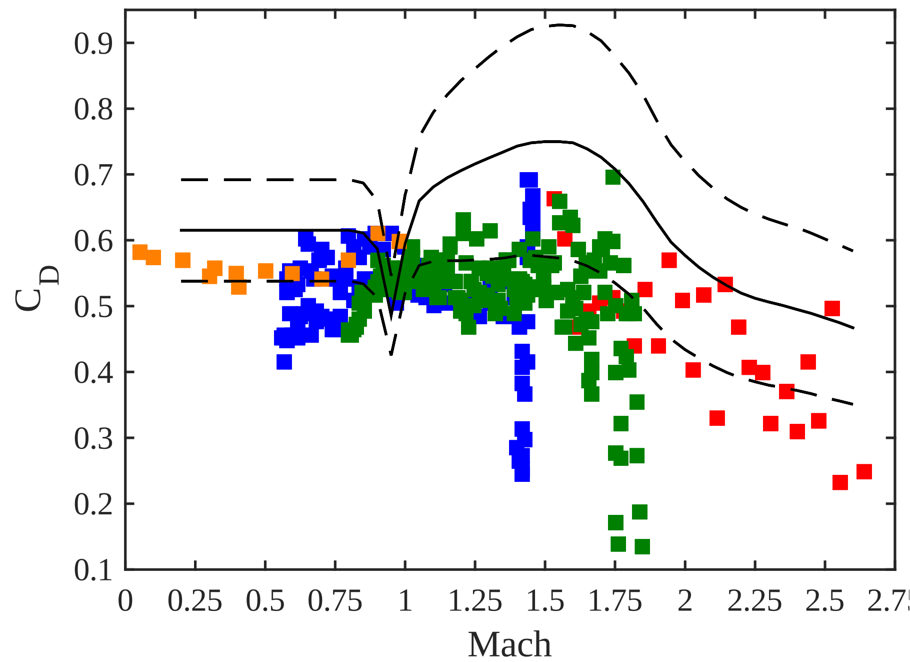
- Currently, nominal simulations yield: t_{inf} ≈ 0.6 s.

Drag Performance

Blunt bodies



Slender bodies



BLDT (L_S = 1.7 $\underline{D_0}$)

Phoenix, MSL (L_S = 1.7 $\underline{D_0}$)

PEPP (L_S = 1.0 $\underline{D_0}$)

All data correspond to flight tests from PEPP, SHAPE, SPED programs (L_S = 1.0 $\underline{D_0}$)

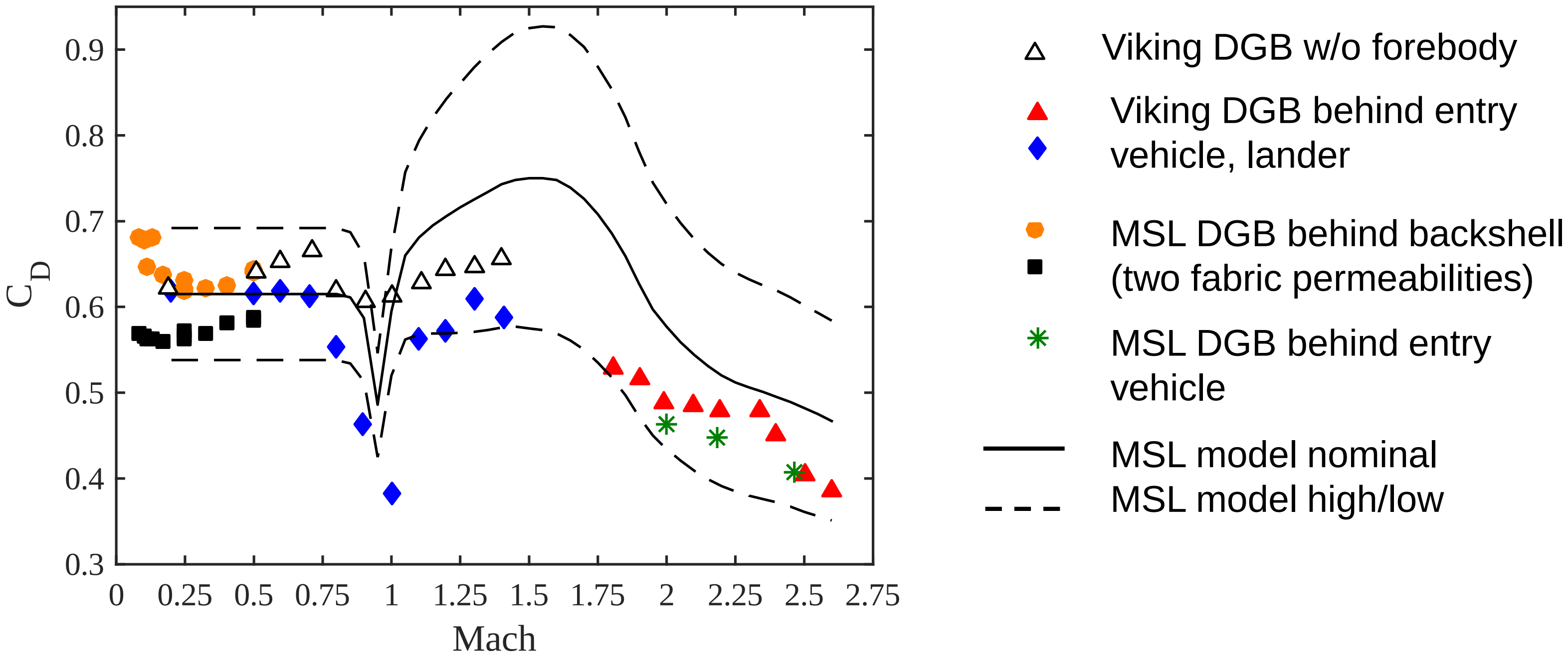
MSL model nominal

MSL model high/low

- MSL model agreement w/all tests of DGBs w/L_S = 1.7 D_0 behind blunt bodies
- C_D of parachutes with L_S = 1.0 $\underline{D_0}$ is lower, regardless of leading body shape
- **No tests of DGBs w/L_S = 1.7 D_0 behind slender bodies**

DGB Wind Tunnel Tests

- A single DGB of MSL-like configuration was wind-tunnel tested behind a slender body by Viking in ’72
- Multiple tests of similar DGBs behind blunt bodies for comparison



- C_D of DGB behind slender sting 5-11% higher than for DGBs behind blunt bodies
- Very small transonic drag crisis for slender body case
- Wind tunnel results approx. 15% lower than C_D measured in flight

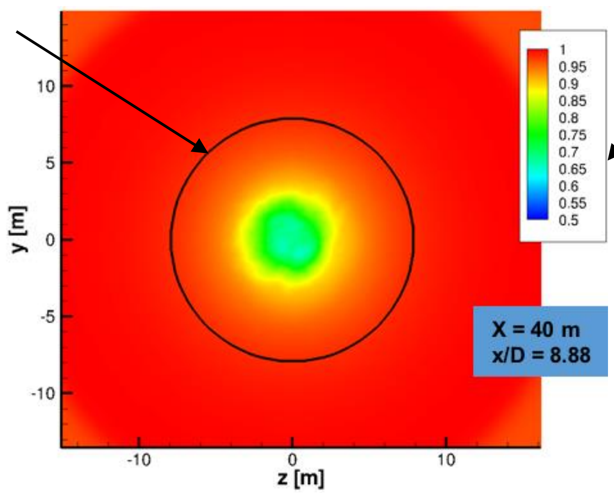
Slender & Blunt Body Wakes

- Time-averaged wake of the leading body at the approximate location of the parachute skirt (40 m behind nose)

Blunt body (MSL config)

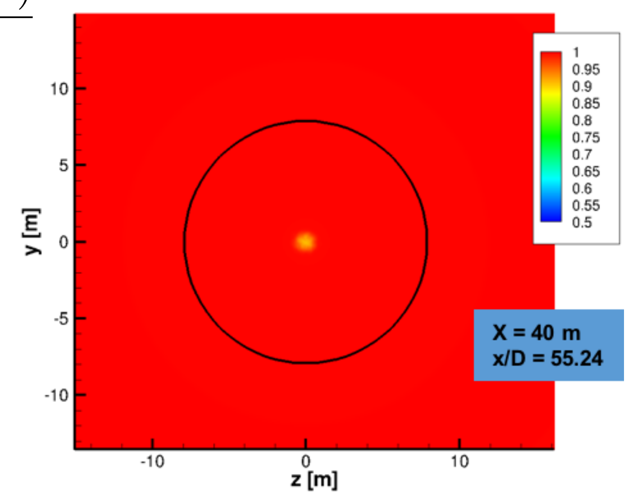
Inflated parachute inlet area

Large wake footprint



$$\frac{q(x,y,z)}{q_\infty}$$

Slender body (ASPIRE)

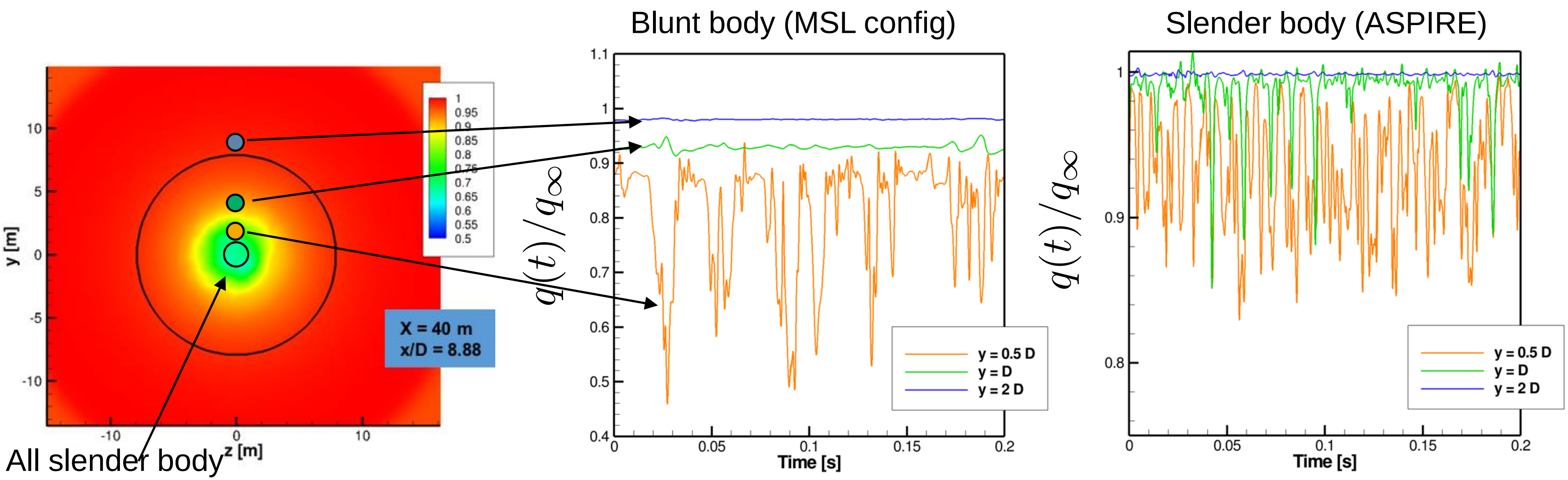


q deficit region << parachute inlet area

- Integrated *q* over parachute inlet area $\int\int_{inlet} q dy dz$ was compared against the freestream equivalent $(q_\infty \pi D_p/4)$
- With parachute aligned with the centerline of the leading body:
  - Blunt body: 92 % of freestream
  - Slender body: > 99% of freestream
- Mean parachute ``pull angle'' for MSL DGB was approx. 4 deg
- Suggests pull angle should make little difference to ASPIRE DGB drag

Temporal Wake Unsteadiness

- Time-varying wake characteristics of the wake:
  - 40 m downstream of vehicle nose
  - 3 probe locations, at increasing distance from the centerline:



All slender body measurements within circle

- Near vehicle centerline, blunt body *q* oscillates between 50% and 90% of freestream
- For slender body, oscillations remain within 15% of freestream
- **Expect larger variations in C_D for DGBs in blunt body wakes**

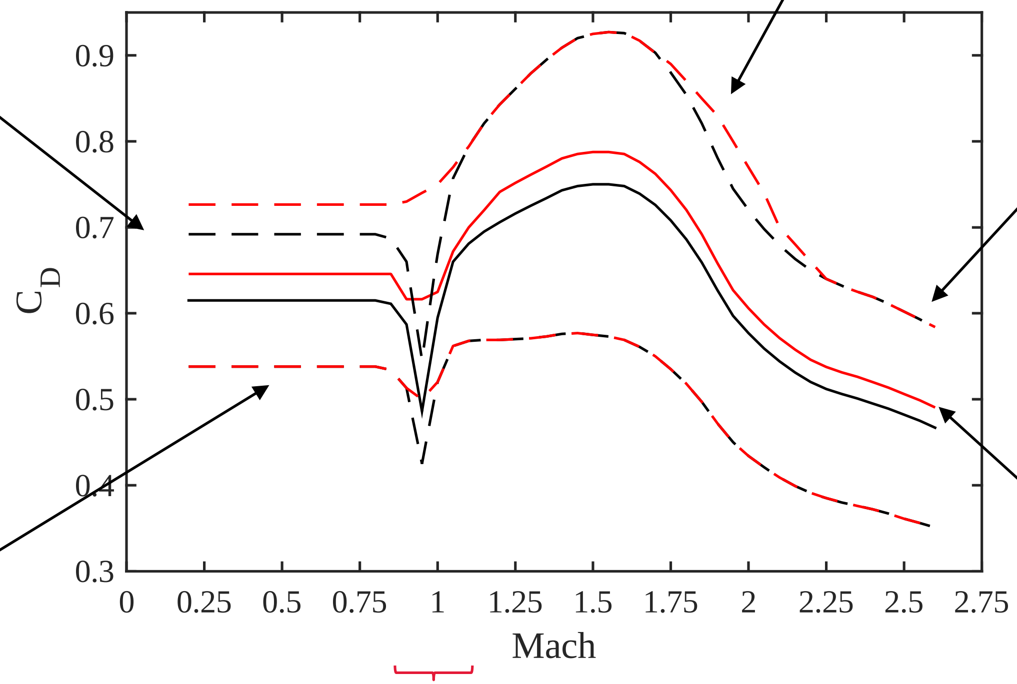
ASPIRE Drag Model

- MSL drag model updated based on historical tests & CFD results:

Additional margin in upper bound @ ASPIRE deployment Mach.

Subsonic mean & upper bound increased 5%. Reflects differences between slender & blunt body wakes in wind tunnel

MSL model slightly overestimates supersonic C_D . Supersonic upper bound mostly unchanged



Subsonic & supersonic lower bound unchanged

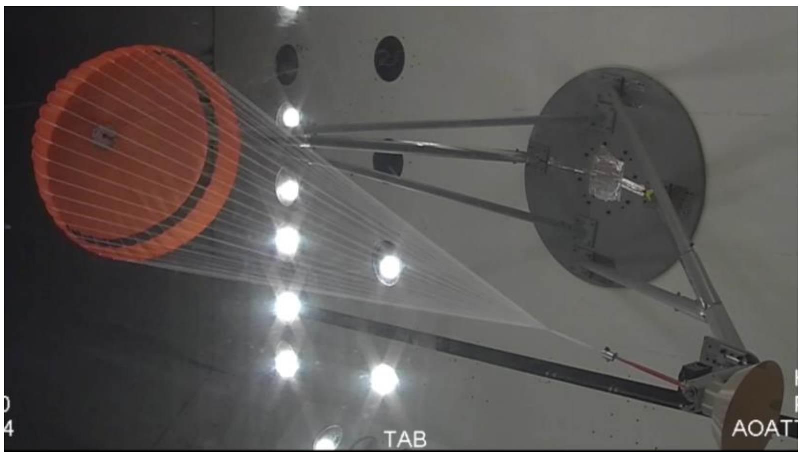
Supersonic mean increased 5%. Reflects between slender & blunt body wakes in wind tunnel & CFD

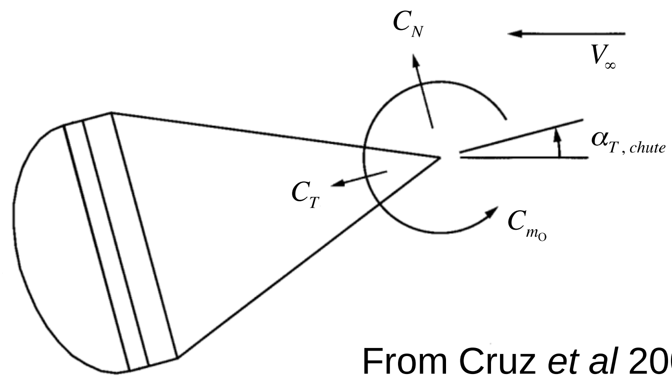
Decreased transonic drag bucket for slender body

MSL nominal — MSL high/low — ASPIRE nominal — ASPIRE high/low

DGB Static Aerodynamics

- Most wind tunnel tests focus on C_D only
- The NESC & the LDSD project conducted a test of the MSL DGB in 2014:
  - Similar to test conducted by MER in 2001 (Cruz *et al*, AIAA 2003-2129)
  - 6.7% scale models of MSL DGB & backshell

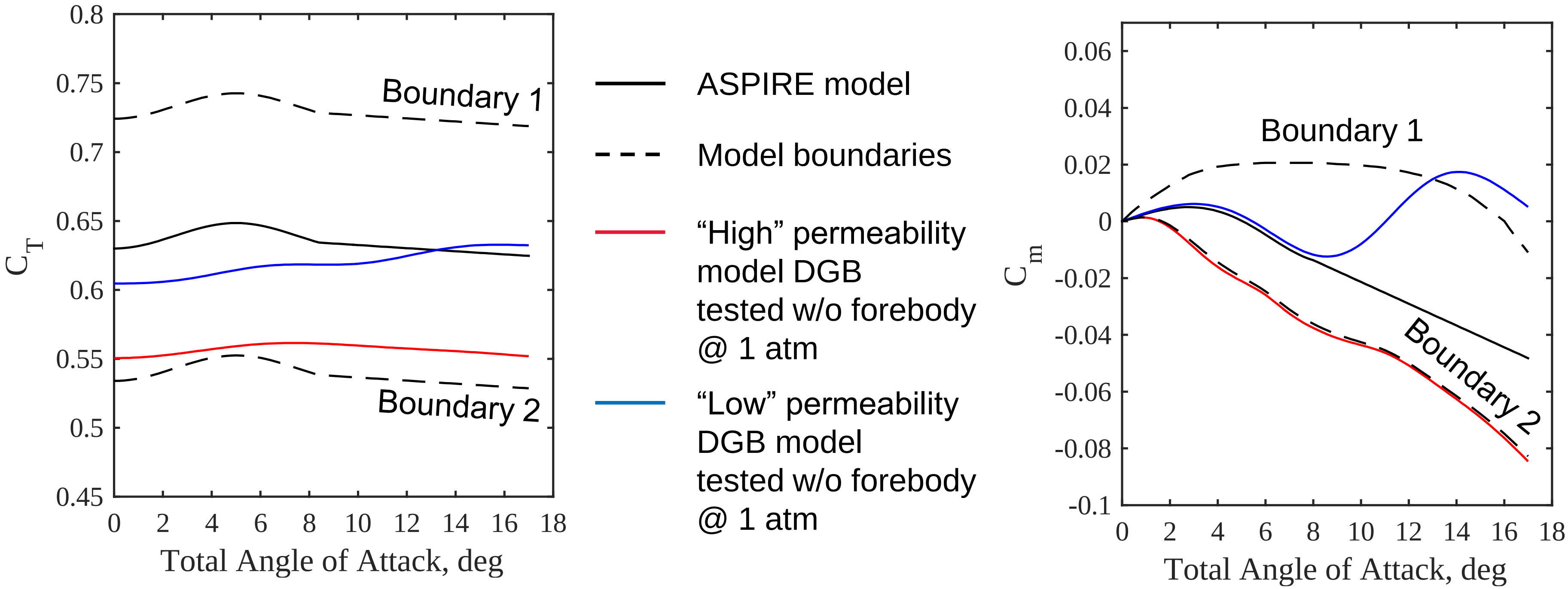




From Cruz *et al* 2003

  - Determined static force & moment coefficients (C_T, C_N, C_{m0}) as a function of angle of attack
  - DGBs tested in the wake of MSL backshell & *without* the backshell
  - Conducted at Langley's Transonic Dynamics Tunnel (TDT):
    - $0.1 < M < 0.5$
    - Static pressure: 0.05 atm to 1 atm
  - DGB models w/two different fabric permeabilities: **effective permeability of ASPIRE DGBs *at test conditions* expected to lie between "low" and "high" permeability fabric**

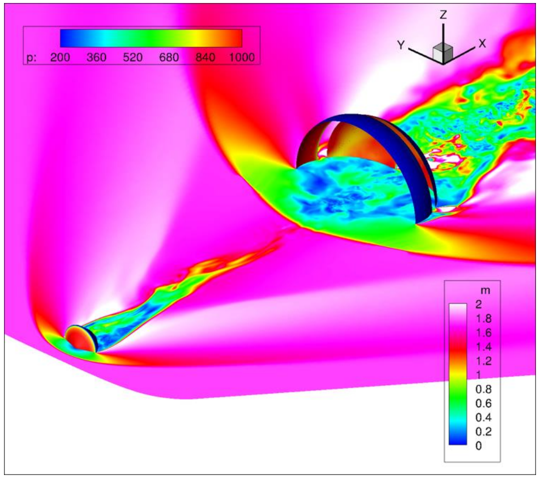
Static Aerodynamics Model

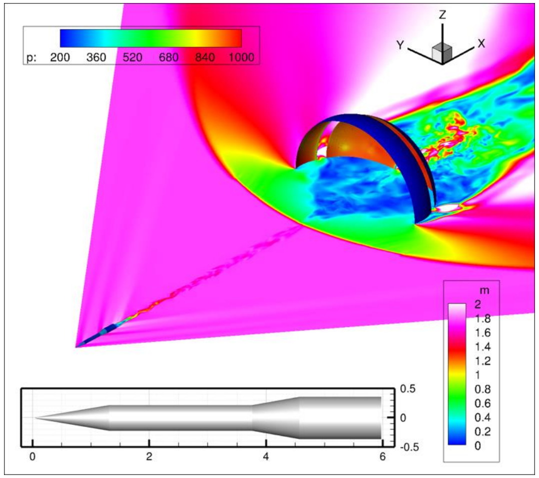


- All aero coefficients dispersed uniformly within two boundaries
- ASPIRE C_T model bounds both "low" and "high" permeability models
  - Results suggest C_T may be higher at lower (ASPIRE-relevant) densities
- C_{m0} model trim angle of attack range spans test results
  - *Negative* pitching moment is stabilizing
  - "High" permeability results provide the most benign stability characteristics
  - "Low" permeability models exhibited second unstable trim angle of attack
  - Results suggest models may be less stable at (ASPIRE-relevant) densities

Summary and Ongoing Work

- Developed models for the deployment, inflation, and performance of the ASPIRE DGBs
- Deployed supersonically in the wake of a slender sounding rocket payload
- Models based on historical tests & CFD simulations of the wakes behind blunt and slender bodies
- Currently developing simulations of a model DGB in the leading body wake:
  - ASPIRE & MSL geometries
  - Rigid, impermeable canopy
  - Preliminary results: canopy bow shock significantly more affected by wake for blunt body geometry





- Future work: consider simulations w/ non-zero parachute pull angle
- Evaluate and update parachute DGB models following first flight
- Examine differences between ASPIRE test & at Mars conditions

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Stay tuned: First ASPIRE flight scheduled for August 1st, 2017!

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