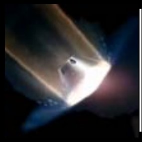

Modeling Heatshield Erosion Due to Dust Particle Impacts for Martian Entries

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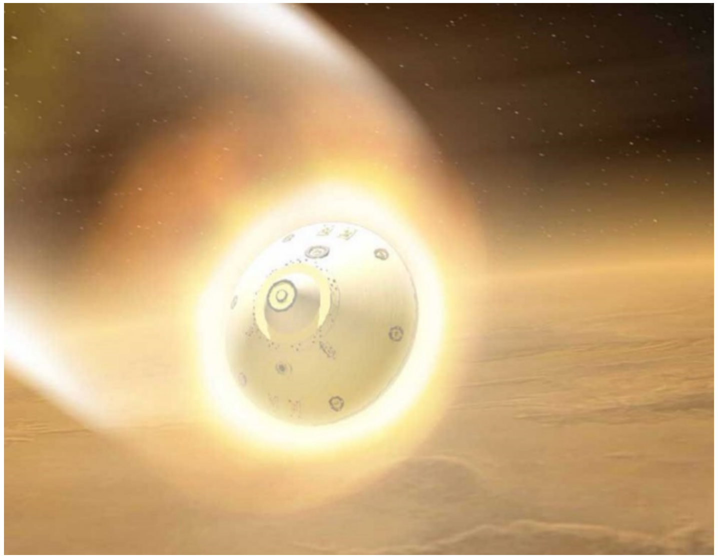
Introduction

- A unique feature of planetary entry into Mars is the possibility of encountering a major regional or global dust storm.
- Major dust storms occur every few years but don't happen at regular intervals.
- Larger (5-10 micron) particles can persist as high as 50 km altitude for 20-50 days after the beginning of a major storm.

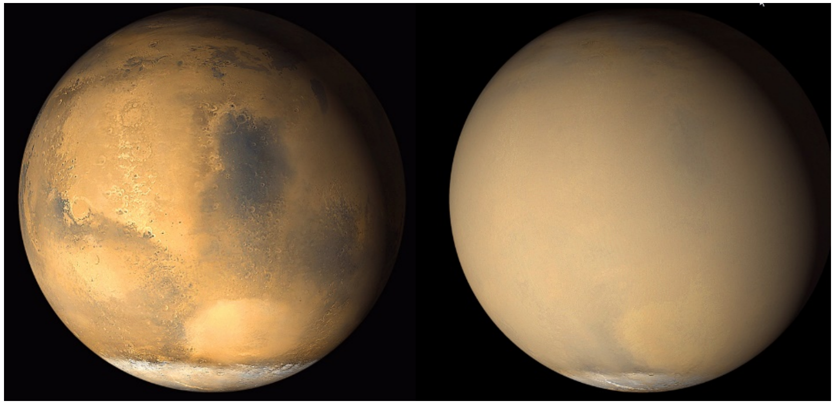


Spacecraft entering Mars during a dust storm.

- Design of the thermal protection system (TPS) for Martian entry should include an estimate of the heatshield erosion due to dust particle impacts. Dust erosion can increase necessary TPS thickness and/or increase risk due to reduced margins.

Major Global and Regional Dust Storms

- Major global dust storms have occurred in 1971, 1973, 1977 (two storms), 1982, 1994, 2001, 2007, and 2018.
  - The 2018 storm disabled the Opportunity rover which had survived the 2007 storm.
  - In 1796 astronomer H. Flaugergues detected “yellow clouds” on Mars that may have been the first observation of a Martian dust storm.
  - G.V. Schiaparelli made observations of Martian dust in the 1870’s.
- Major regional dust storms happen more frequently.
  - A regional dust storm in November 2012 covered much of the Southern Hemisphere.



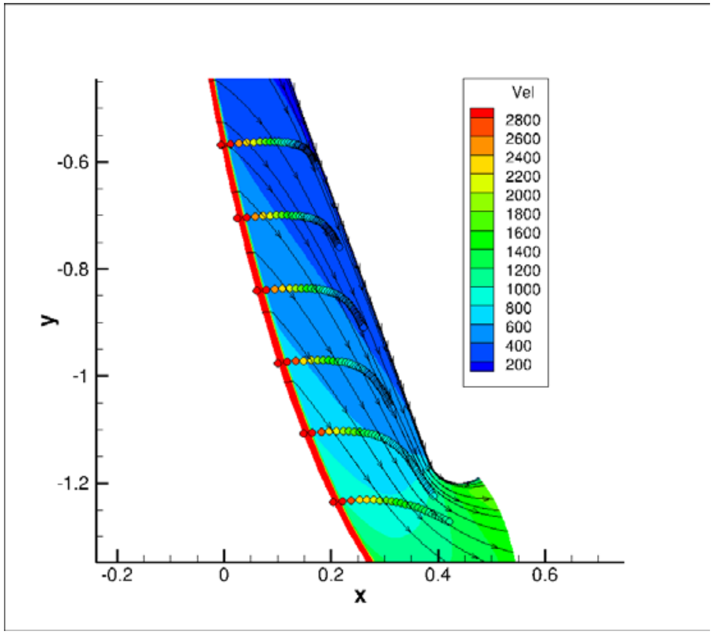
Mars before and during the 2018 global dust storm.

Motivations for this Work

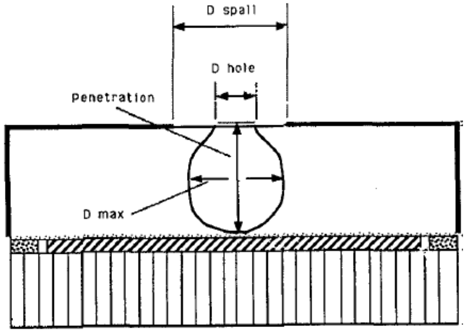
- Heatshield erosion due to dust particle impacts is a multi-disciplinary analysis based on research papers that go back to the 1960’s.
  - Some of the older papers are difficult or impossible to find.
  - Many of the older papers use a mixed system of units – sometimes they don’t indicate what the units are.
  - Some of the derivations in previous references have errors, which are only apparent by going through the full derivation of the equations.
- This paper brings everything needed to perform analysis of heatshield erosion due to dust particle impacts into a single, consistent reference.
- There is a lot of detail in the paper (33 pages, 56 equations, etc.). Only selected highlights will be discussed in this talk.

Dust Particle Erosion Processes

- Dust particles enter and travel through the shock layer.
  - Shock layer flow alters particle trajectories.
  - Particles slow down and heat up.
  - Impact of shock layer on particles a function of the particle size, velocity and composition.
- If particles strike heatshield with sufficient energy, spallation damage occurs.
- Cumulative effect from all particle impacts along entry trajectory defines total heatshield erosion from particle impacts.



Particle velocity during shock layer trajectory



Schematic of particle impact crater

Dust Particle Erosion Solution Process

- **Determine the dust environment.**
  - **Dust particle size distribution.**
  - **Particle number density.**
  - **How dust environment changes with altitude.**
- Compute particle trajectories as they travel through the shock layer.
  - Objective: Determine size, velocity, and number density at impact at multiple points along entry trajectory.
- Identify appropriate particle impact damage correlations.
  - Presumably based on best available experimental data.
- Compute heatshield erosion due to dust particle impacts along entry trajectory.

Dust Particle Shape

- Toon, Pollack,and Sagan (1977) deduced from 1971-72 dust storm data, that the shape of Martian dust particles were plate-like.
- However, most if not all previous research assumes that dust particles are spherical.
  - Allows the particle mass to be related to particle radius and/or diameter.
  - Particle drag coefficients can based on experimental data on spherical projectiles.
  - Allows particle surface area (needed for heat transfer) to be related to radius and/or diameter.
  - No need to evaluate particle orientation.
- This study assumes that the Martian dust particles are spherical.

$$m_p = \frac{4}{3}\pi r_p^3 \rho_p = \frac{1}{6}\pi d_p^3 \rho_p \qquad A_s = 4\pi r_p^2 = \pi d_p^2$$

Dust Particle Size Distribution

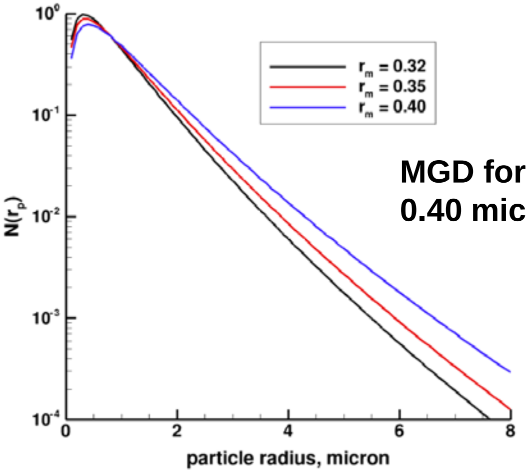
- Most researchers assume a *modified gamma distribution* (MGD) function to model Martian dust particle size distribution.

$$N(r_p) = N_0 r_p^2 exp\left(-4\left({r_p}/{r_m}\right)^{0.5}\right)$$

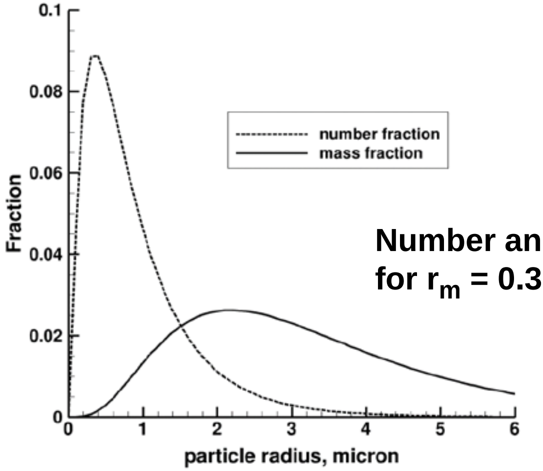
$r_p =$ Particle radius

$r_m =$ Mode radius

- Decreasing mode radius shifts gamma distribution curve to the left increasing number of smaller radius particles.
- MGD can be used to compute the number and mass fractions as a function of particle radius



MGD for r_m = 0.32, 0.35, and 0.40 microns.



Number and mass fractions for r_m = 0.35 micron

Mass Mixing Ratio

- The mass mixing ratio, q, is the ratio of the mass of all dust particles per unit volume divided by the mass of atmospheric gas per unit volume.
- Mass mixing ratio can be related to the dust opacity, $d_z\tau$.

$$q = \frac{4}{3}\frac{\rho_p}{Q_{ext}}\frac{d_z\tau}{\rho}r_{eff}$$

ρ_p = dust particle density

ρ = atmospheric density

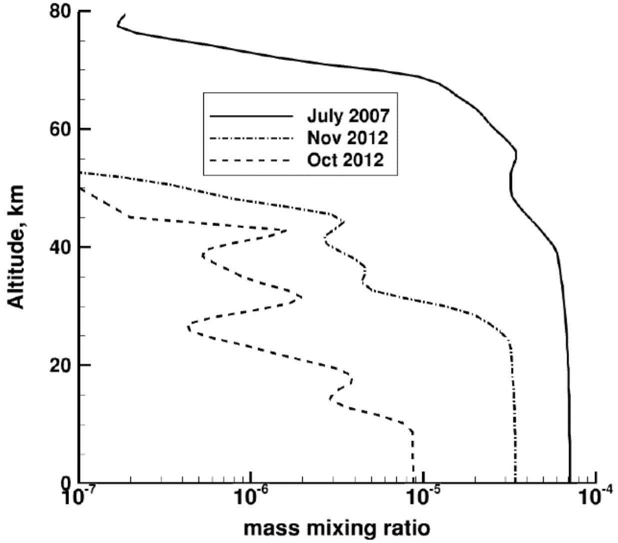
r_{eff} = effective particle radius

Q_{ext} = extinction coefficient

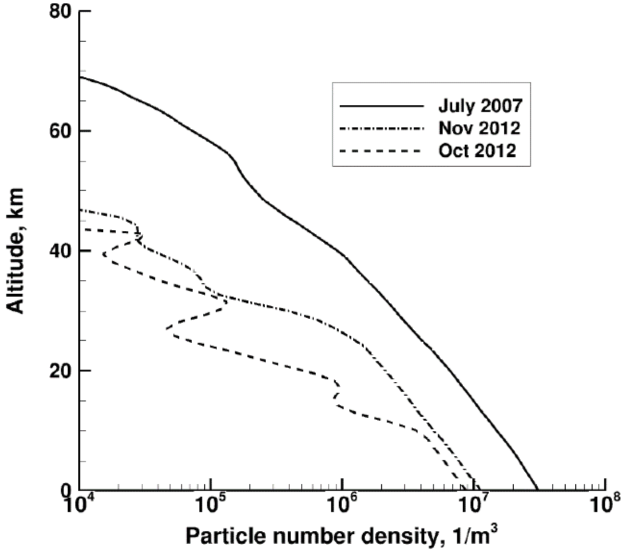
- Before 2006, most researchers assumed an exponential decay of *q* with altitude.
- The Mars Climate Sounder (MCS) system on the Mars Reconnaissance Orbiter (MRO) has been making observations in Martian atmosphere since 2006 that include vertical profiles of temperature and dust opacity, $d_z\tau$.
- Mass mixing ratio and particle number density as a function of altitude can be computed from the MCS data.

Dust Environments

- MCS data for three dust environments used in this study:
  - 2007 global dust storm
  - November 2012 regional dust storm
  - October 2012 quiescent dust conditions.
- At 20 km altitude, the 2007 storm had 25x the amount of dust (by mass) compared to quiescent dust conditions.



Mass mixing ratio as a function of altitude



Particle number density as a function of altitude.

Dust Particle Erosion Solution Process

- Determine the dust environment.
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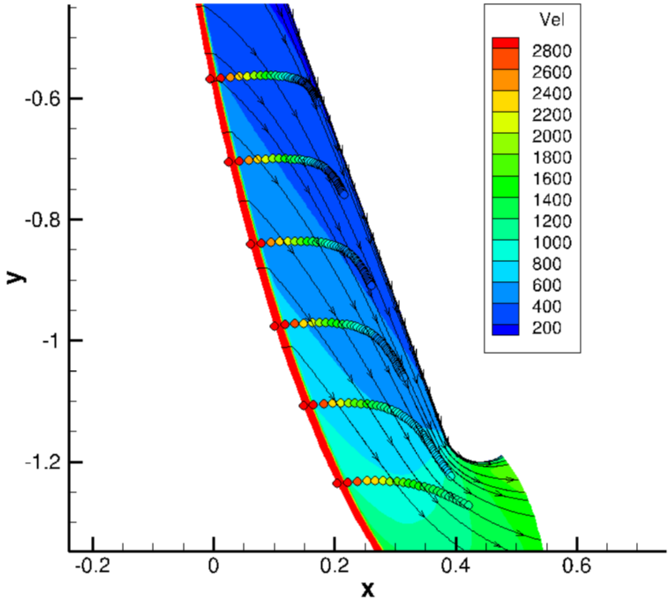
  - Presumably based on best available experimental data.
- Compute heatshield erosion due to dust particle impacts along entry trajectory.

Particle Trajectory Analysis

- The particle trajectories must be computed from the bow shock, through the shock layer, until they impact the heatshield (or not).
- Shock layer flow will cause particles to slow down, heat up, and may bend particle trajectories.
- Martian dust particles are small enough that they will typically be in a non-continuum flow regime.
- One-way particle-fluid coupling used in this study – shock layer flow affects particles but particles do not affect shock layer flow.
  - Shock layer flow and particle trajectories can be computed independently of each other.



Particle Trajectories: One-way Coupling

- Particle trajectories through the shock layer computed using a Lagrangian technique by solving a coupled set of ODEs.

- Function of both particle and surrounding fluid properties.
- Particles started at locations along the outer boundary of CFD grid.
- Equations integrated until particle strikes heatshield or is pushed around vehicle.

Particle location: $$\frac{dx_p}{dt} = u_p$$

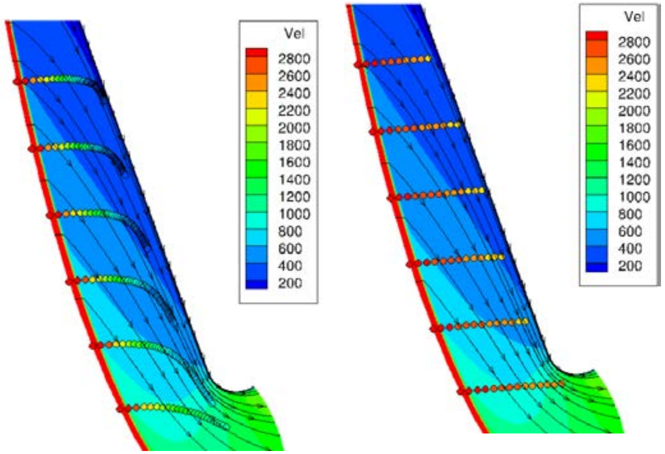
$$\frac{dy_p}{dt} = v_p$$

Particle velocity: $$\frac{d\overrightarrow{V_p}}{dt} = \frac{3}{4}\frac{\rho_g}{\rho_p}\frac{C_D}{d_p}\left|\Delta\vec{V}\right|\Delta\vec{V}$$

Particle temperature: $$\frac{dT_p}{dt} = \frac{6C_h}{\rho_p c_p d_p}\left(T_g - T_p\right)$$

Particle diameter: $$\frac{d\left(d_p\right)}{dt} = \frac{2C_h\left(T_g - T_{vap}\right)}{\zeta\rho_p}$$

Particle velocities overlaid on shock-layer velocity.



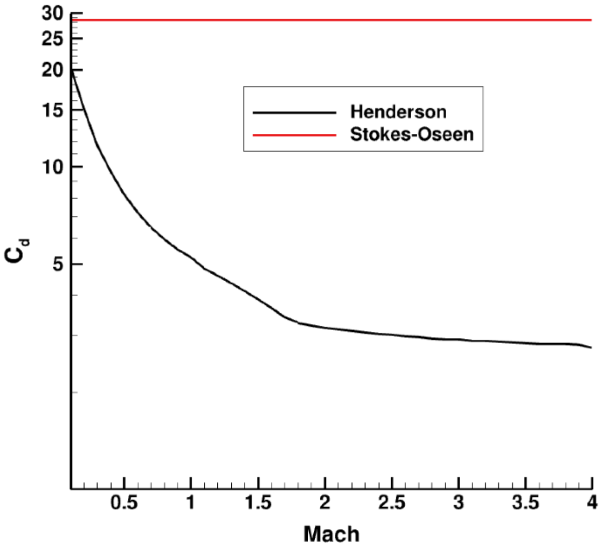
1-micron particles **5-micron particles**

Non-Continuum Effects: Drag Coefficient

- Key to solving the particle velocity equation is to accurately evaluate the particle drag coefficient, C_D.

$$\frac{d\overrightarrow{V_p}}{dt} = \frac{3}{4}\frac{\rho_g}{\rho_p}\frac{C_D}{d_p}\left|\Delta\vec{V}\right|\Delta\vec{V}$$

- Particle drag correlation must account for non-continuum effects.
  - This study uses the Henderson drag correlation (1976).



Continuum correlations will over-predict particle drag coefficient – particles will slow down too much.

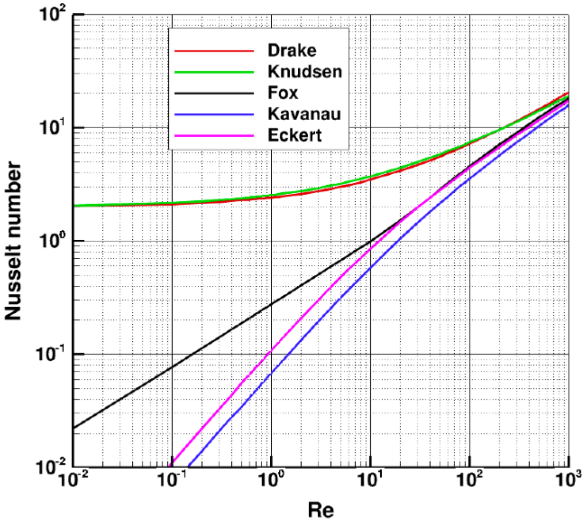
Ongoing research at the University of Minnesota and elsewhere to update the Henderson correlation.

Non-Continuum Effects: Nusselt Number

- Key to heat transfer to the particle is to accurately evaluate the heat transfer coefficient, C_h, that is related to the Nusselt number.

$$\frac{dT_p}{dt} = \frac{6C_h}{\rho_p c_p d_p}\left(T_g - T_p\right) \qquad Nu = \frac{C_h d_p}{\kappa_g}$$

- Nusselt number correlation must account for both non-continuum effects and be applicable for supersonic particle Mach numbers.
  - This study uses the Fox Nusselt number correlation (1977).



Continuum flow correlations (Drake, Knudsen) over-estimate Nusselt number.

Subsonic correlations (Kavanau, Eckert) under-estimate Nusselt number.

Dust Particle Erosion Solution Process

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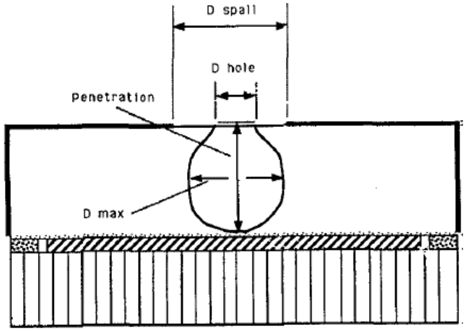
- **Identify appropriate particle impact damage correlations.**
  - **Presumably based on best available experimental data.**
- Compute heatshield erosion due to dust particle impacts along entry trajectory.

Particle Impact Damage Models

- When a dust particle strikes the heatshield with sufficient energy, the resulting impact crater will cause surface erosion.
- A lot of information on particle damage models can be found in the paper. Only a brief overview given here.
- Existing impact damage models based on experiments using projectiles typically much larger than Martian dust particles.
- Experiments performed in one of two ways:
  - Measured crater diameter and penetration from individual (or several) particle impacts.
  - Total mass loss measured due to all particle impacts during an experiment.
- Greely and Schulz (1974) study on impact cratering found that crater diameter, D_c, is proportional to the cube root of particle kinetic energy at impact.

$$D_c = C\rho_p^{1/3} d_p {v_p}^{2/3}$$

- This paper provides surface damage correlations for five TPS materials: fused-silica, Space Shuttle tiles, AVCOAT, cork, and Norcoat Liège



Schematic of particle impact crater

Dust Particle Erosion Solution Process

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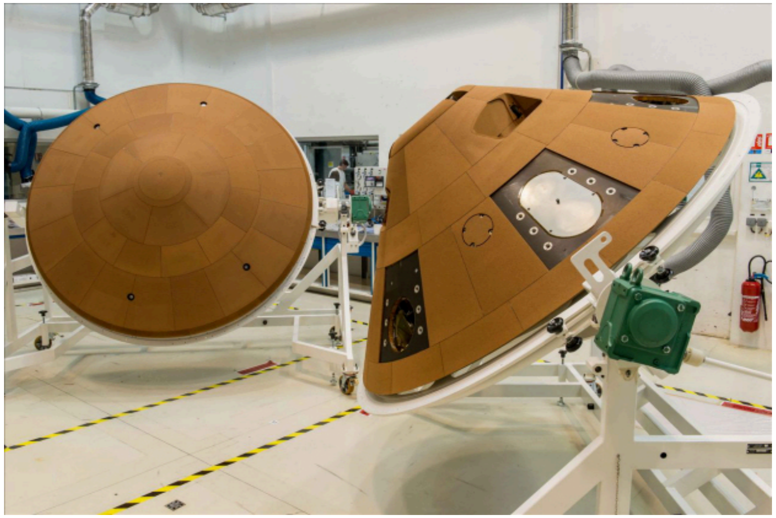
- **Compute heatshield erosion due to dust particle impacts along entry trajectory.**

Schiaparelli Entry Capsule

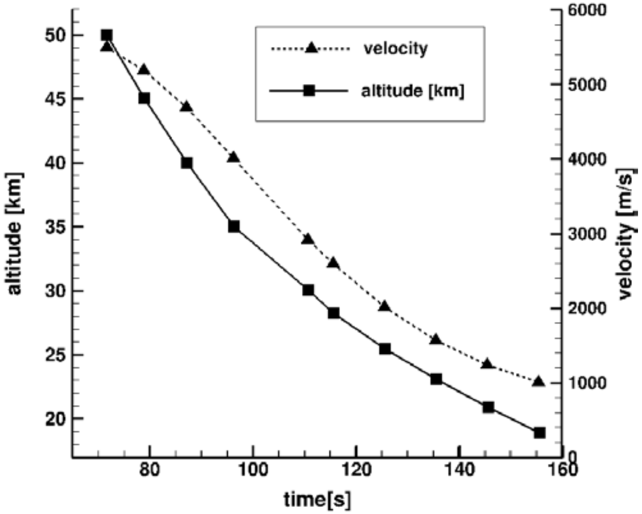
- One-way coupling technique tested by computing the theoretical heatshield erosion due to dust particle impacts for the ExoMars Schiaparelli Entry capsule.
- 2.4 m diameter, 70-deg sphere cone capsule entered the Martian atmosphere in October 2016.
  - One of the mission goals was to enter during a dust storm to perform atmospheric and surface measurements (didn’t happen).
- Schiaparelli heatshield TPS: Norcoat Liège insulating tiles – cork particles infused with phenolic resin.
- The surface damage correlation for Norcoat Liège developed in this study was used to compute dust particle erosion.



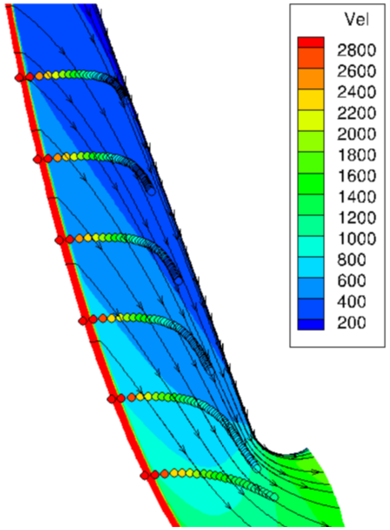
Schiaparelli capsule heatshield

Shock Layer Flow Solution – DPLR CFD

- Shock layer flow solutions computed using the DPLR v4.04.0 Navier-Stokes flow solver at 9 points along Schiaparelli entry trajectory.
  - Altitudes range from 20 – 50 km, where most dust erosion occurs.
  - 8-species [CO_2, CO, N_2, O_2, NO, C, N, O] finite-rate chemistry.
  - Two-temperature (T-Tv) thermochemical nonequilibrium.
  - Shock layer fluid values extracted – density, velocity, temperature, pressure, viscosity, thermal conductivity, Prandtl number, specific heat.



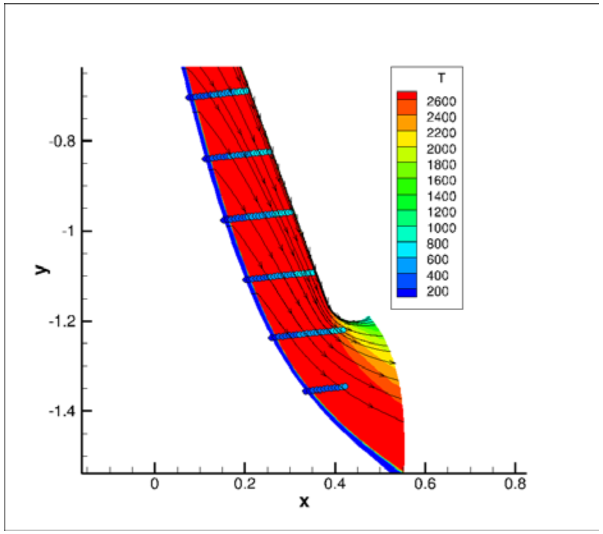
Schiaparelli trajectory points



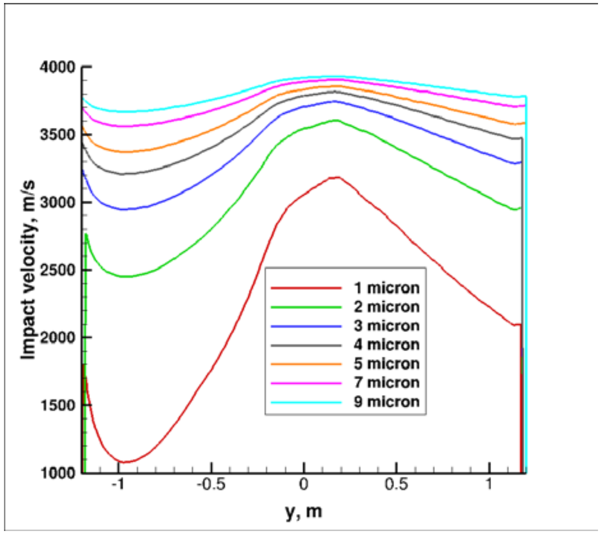
DPLR shock layer flow solution, 30 km altitude

Particle Impact Results

- Particle trajectories were computed along Schiaparelli trajectory.
  - 15 particle sizes, 9 trajectory points
  - Particles started at equidistant locations along CFD grid outer boundary.
  - Particle impact velocity and diameter data provided to Icarus material response code.
  - Smaller particles more influenced by the flow – slow down and heat up more. None of the particles reached the vaporization temperature.



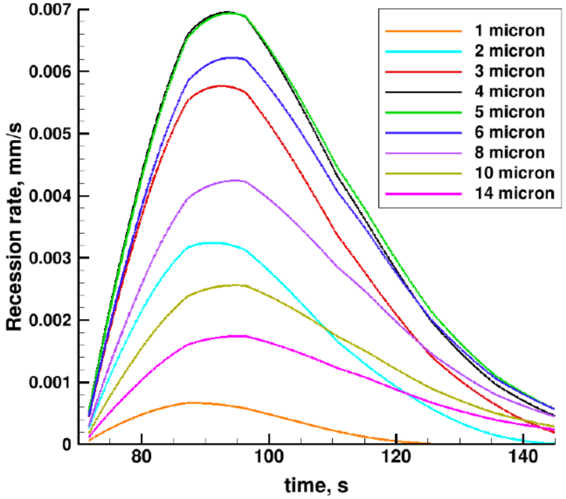
Temperature contours, 5-micron diameter particles traveling through 30 km altitude shock layer flow



Particle impact velocity along heatshield surface, 30 km altitude.

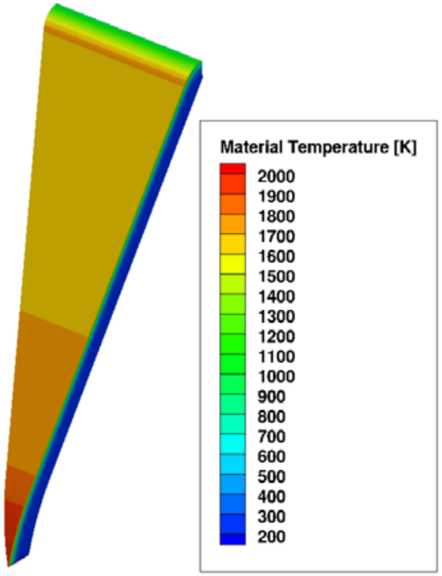
Icarus Material Response Code

- Icarus is a 3-D, finite-volume, unstructured material response solver developed at NASA Ames.
- CFD and particle trajectory inputs used by Icarus to compute material response along Schiaparelli entry trajectory between 50 and 20 km.
- TPS surface erosion computed due to thermochemical ablation and dust particle impacts



Greatest impact erosion caused by 4- and 5-micron particles

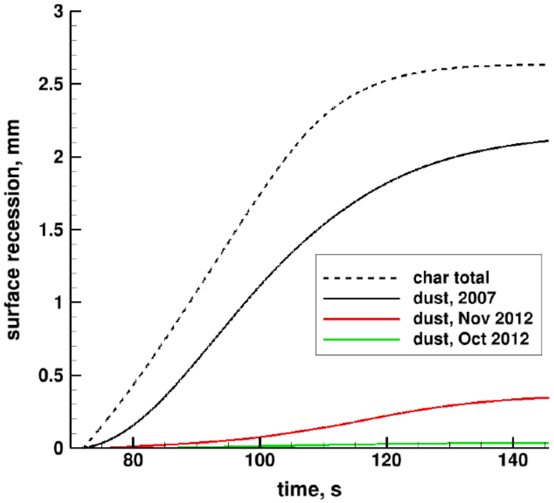
Surface recession rates as function of particle diameter, 2007 global dust storm conditions.



Temperature contours, Schiaparelli 50 km trajectory point

Cumulative Heatshield Recession

- Cumulative surface recession computed due to thermochemical ablation (charring) and dust particle impacts.
- Nominal Schiaparelli heatshield TPS thickness = 12.4 mm.
- Estimated dust erosion at 2007 global dust storm conditions of 2.1 mm is 17% of nominal heatshield thickness.
- Dust erosion less important for November 2012 regional dust storm conditions and negligible under quiescent dust conditions.



Condition	Recession, mm
Char	2.6
Dust, 2007	2.1
Dust, Nov 2012	0.35
Dust, Oct 2012	0.04

Cumulative stagnation point surface recession.

Concluding Remarks/Future Work

- This presentation gave an overview of a paper that is intended to provide a single, consistent reference that covers all aspects of estimating heatshield erosion due to dust particle impacts.
  - Characterizing the dust environment: particle size distribution and mass mixing ratio and how these quantities vary with altitude.
  - Computing the particle trajectories through the shock layer.
  - Presentation of surface damage correlations for 5 TPS materials.
  - Summing up the individual particle impacts over the entry trajectory to obtain the cumulative heatshield recession.

Concluding Remarks/Future Work

- A techniques described in this paper were applied to compute surface recession due to dust particle impacts on the Schiaparelli capsule at three dust conditions obtained from MCS data.
- Under 2007 global dust storm conditions, Cumulative stagnation point heatshield recession due to dust particle impacts was estimated to be 2.1 mm, which corresponds to 17% of the nominal TPS thickness.
- Future work will include comparing these one-way coupling results against values from a two-way coupling code.
- New damage correlations will be derived based on upcoming experimental data from the German Aerospace Center (DLR) using particle sizes more representative of Martian dust.

Acknowledgements

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Backup Slides

- Backup Slides

Particle-Fluid Coupling

- Different approaches to couple the particle trajectories and shock layer fluid.
- Zero coupling.
  - Particles strike heatshield at freestream velocity – only valid for large particles and/or low density.
- One-way coupling.
  - Shock layer flow affects particle trajectories but particles do not affect shock layer flow.
  - Solutions computed independently of each other.
  - Shock layer computed first. Flow solution used to compute particle trajectories.
  - Example: This study
- Two-way coupling.
  - Particles and shock layer flow exchange momentum and energy – they affect each other.
  - Shock layer flow and particle trajectories computed at the same time.
  - Can model things that one-way coupling cannot, e.g. heating augmentation due to particle impacts.
- Four-way coupling.
  - Particle collisions are modeled. Particles can rebound off heatshield and affect shock layer flow.
  - Four-way coupling collisions framework not discussed in this paper.

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