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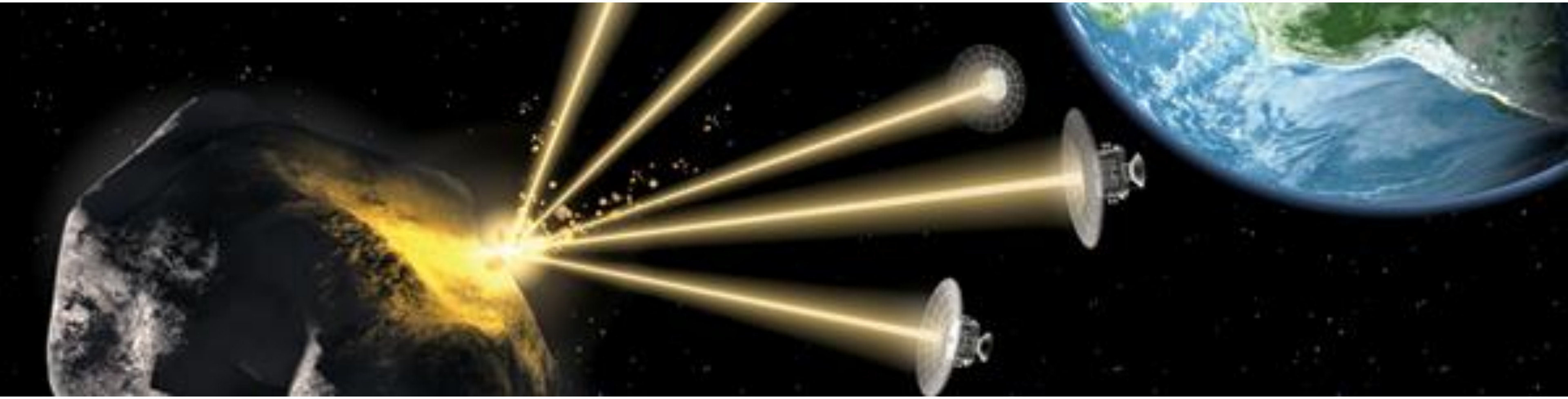

Space Debris and Asteroids (Re)Entry Analysis Methods and Tools

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Outline

- (Re)-Entry and Hypersonic Flows
  - Introduction to flow regimes and hypersonic phenomena (shock waves and heating)
- Re-entry and evolution of Space Debris
  - Introduction (statistics, and hazard & risk assessment)
  - Main tools and used methods
- Entry and evolution of Asteroids/Comets
  - Introduction
  - Main methods and some recent advances

Introduction

- "A space vehicle/object entering the atmosphere of a planet passes different flow regimes", that is "The flow field surrounding a vehicle/object ***evolves*** as it descends to the surface of a planet."

- **The reason for that lies in:**
  - the large velocity of the entering vehicle/objects ($\approx$ 7.5 km/s for re-entry from Earth orbits and $\geq$ 10 km/*s* for planetary entries … up to 20-70 km/s for asteroids/comets), and
  - the wide range of density and pressure with the altitude.

Introduction

- the large velocity of the entering vehicle/objects (≈ 7.5 km/s for re-entry from Earth orbits and $\geq$ 10 km/*s* for planetary entries … up to 20-70 km/s for asteroids/comets), means evolution from

Hypersonic flow

to

Supersonic (<u>not always </u>…)

and finally

Subsonic (<u>not always </u>…)

Introduction

- The wide range of density and pressure with the altitude, means evolution from

Free molecular flow

to

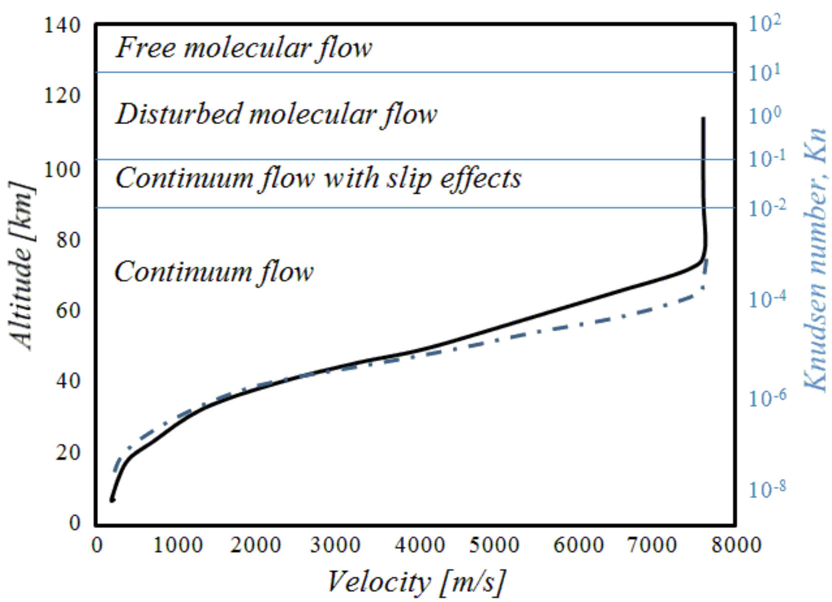
Disturbed molecular flow
(Transition regime)

to

Continuum flow with slip effects

to

Continuum flow



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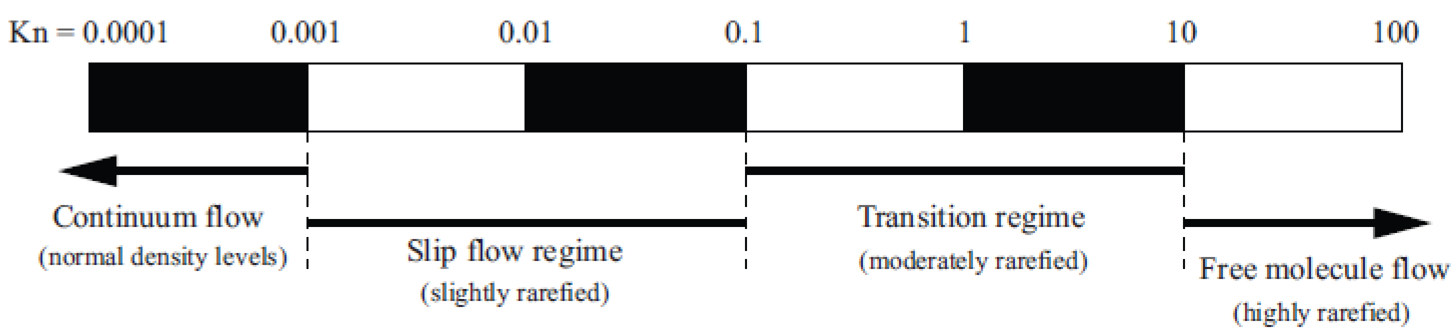
Introduction

- The degree of rarefaction is defined by the Knudsen number

$$Kn = \frac{\lambda}{L}$$

- λ is the molecular mean free path (average value of the path length between two collisions with other molecules)
- L is the characteristic length scale of the considered system



C. White, 2013.

Introduction

- The wide range of density and pressure with the altitude, means evolution from

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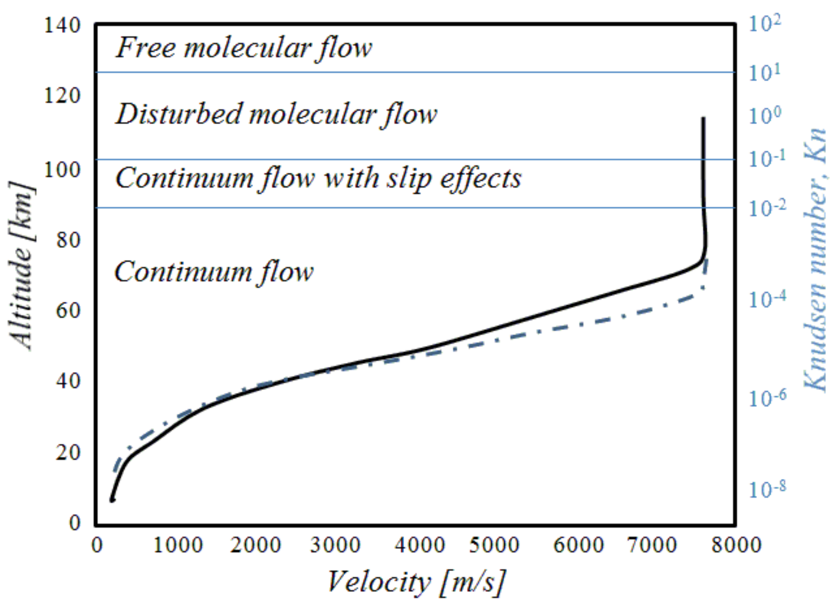
Continuum flow



The two regimes with continuum flow, can be treated with the **Navier-Stokes equations** and differ only with respect to the formulation of the wall boundary conditions.
In the nominal case of continuum flow no-slip conditions at the wall are prescribed, whereas in the second case the **flow slips on the surface** and the temperature of the wall is different from the temperature of the gas at the wall (**temperature jump condition**).

Introduction

- The wide range of density and pressure with the altitude, means evolution from

Free molecular flow

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Disturbed molecular flow (Transition regime)

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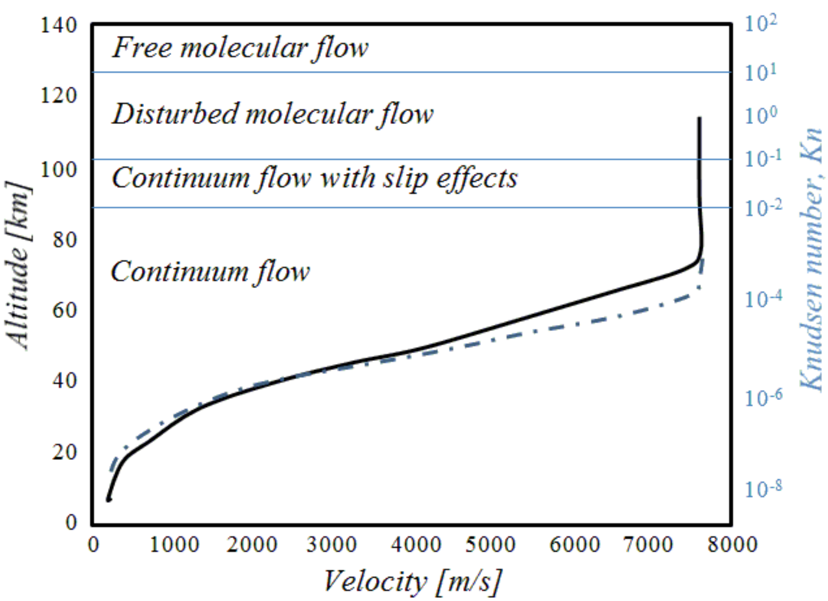

The two molecular regimes requires the application/solution of the **Boltzmann equations** describing the gas kinetic behaviour of flows. Boltzmann equations, in the context of the re-entry flow problem, are usually solved by methods such as the Direct Simulation Monte-Carlo method (DSMC method)

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Introduction

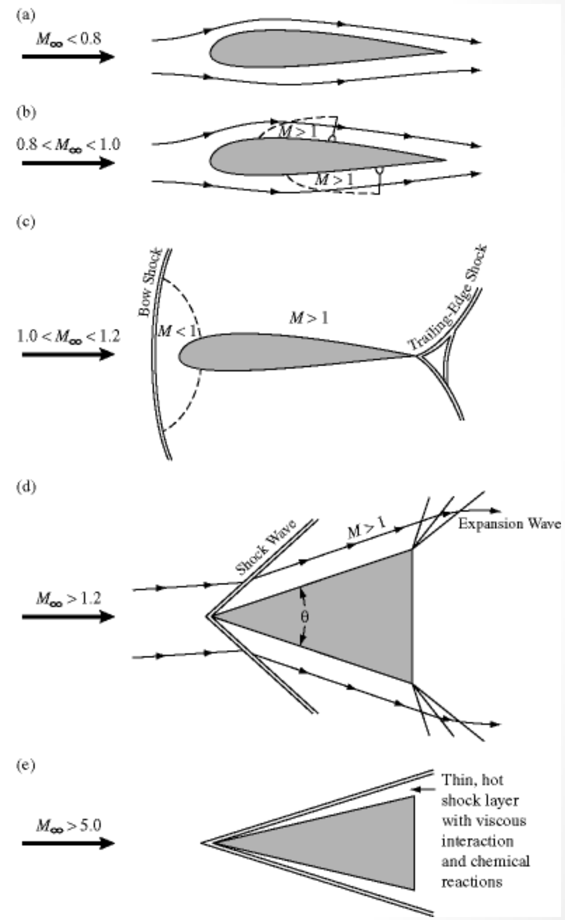
Definition/characterisation of hypersonic flows

$M_\infty < 1$, subsonic flow (perturbations in the flow propagate both downstream and upstream)

$M_\infty > 1$, supersonic flow (perturbations in the flow propagate only downstream)

$0.8 < M_\infty < 1.2$, transonic region

M = speed to sound speed ratio (Mach number)



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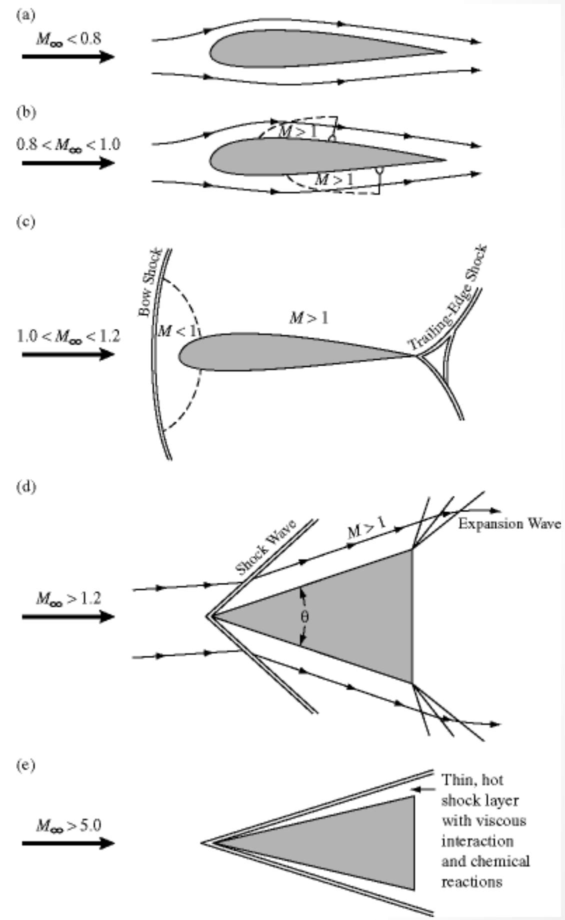
Introduction

Definition/characterisation of hypersonic flows

Shock waves generated for $M_\infty > 0.8$:

Shock waves are very small regions in the gas where the gas properties change by a large amount.



Hypersonic Flows

Definition/characterisation of hypersonic flows

- Across a shock wave, the static pressure, temperature, and gas density increase “very fast”.
- **Equations for Normal shock waves** (shock wave is perpendicular to the flow direction) derived by considering the conservation of mass, momentum, and energy for a compressible gas while ignoring viscous effects.

$$\frac{p_1}{p_0} = \frac{2\gamma M_0^2 - (\gamma - 1)}{\gamma + 1}$$

$$\frac{T_1}{T_0} = \frac{\left[2\gamma M_0^2 - (\gamma - 1)\right]\left[(\gamma - 1) M_0^2 + 2\right]}{(\gamma + 1)^2 M_0^2}$$

$$\frac{\rho_1}{\rho_0} = \frac{(\gamma + 1) M_0^2}{(\gamma - 1) M_0^2 + 2}$$

Specific heat ratio, $\gamma \approx 1.4$ (actually function of temperature)

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Hypersonic Flows

Definition/characterisation of hypersonic flows

- Since shock waves do no work, and there is no heat addition, the total enthalpy and the total temperature are constant.
- Since the flow is non-isentropic, the total pressure downstream of the shock is always less than the total pressure upstream of the shock.
- **Equations for Normal shock waves** (shock wave is perpendicular to the flow direction) derived by considering the conservation of mass, momentum, and energy for a compressible gas while ignoring viscous effects.

$$\frac{p_{t1}}{p_{t0}} = \left[\frac{(\gamma+1)M_0^2}{(\gamma-1)M_0^2+2}\right]^{\frac{\gamma}{\gamma-1}} \left[\frac{\gamma+1}{2\gamma M_0^2-(\gamma-1)}\right]^{\frac{1}{\gamma-1}}$$

$$\frac{T_{t1}}{T_{t0}} = 1$$

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Hypersonic Flows

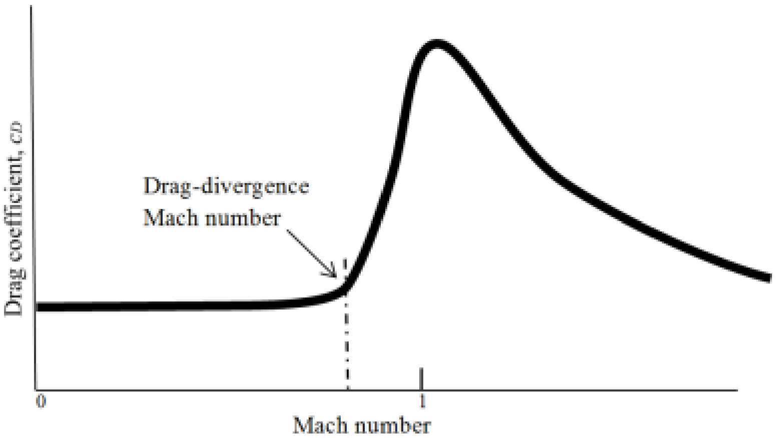
Definition/characterisation of hypersonic flows

- The Mach number and speed of the flow also decrease across a shock wave.
- **Equations for Normal shock waves** (shock wave is perpendicular to the flow direction) derived by considering the conservation of mass, momentum, and energy for a compressible gas while ignoring viscous effects.

$$M_1^2 = \frac{(\gamma - 1)M_0^2 + 2}{2\gamma M_0^2 - (\gamma - 1)}$$

Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- Change from subsonic to supersonic conditions is quite sharp.



Hypersonic Flows

- **Definition/characterisation of hypersonic flows**

- Hypersonic aerodynamics is much different than the now conventional and experienced regime of supersonic aerodynamic.
- **"Rule of thumb":** hypersonic if Mach number >5
- Hypersonic flow is *best* defined as the regime where *certain physical phenomena* become progressively more important as the Mach number is increased to higher values (some phenomena may become important before reaching 5, other much after … no crisp threshold)

J. Anderson, HYPERSONIC AND HIGH TEMPERATURE GAS DYNAMICS, McGraw-Hill Book**, 1989.**

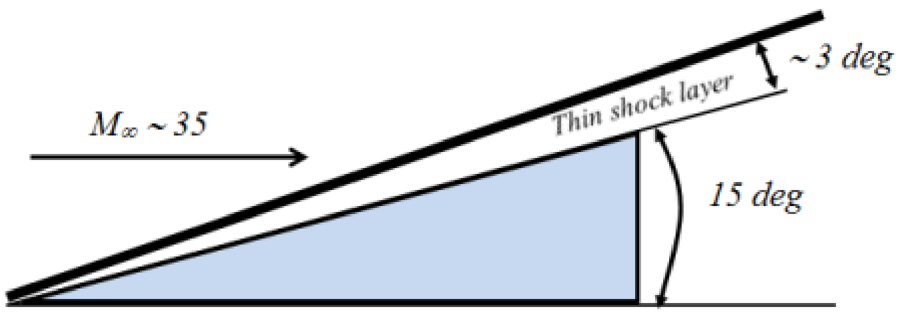
Hypersonic Flows

- **Definition/characterisation of hypersonic flows**

- **Thin shock layers**

The flow field between the shock wave and the body is defined as the <u>**shock layer**</u>, and for hypersonic speeds this shock layer can be quite thin.

Some physical complications, such as the **merging of the shock wave itself with a thick, viscous boundary** layer growing from the body surface.



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Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- **Viscous interaction**

Viscous dissipation: high kinetic energy is transformed (in part) into internal energy. Consider as boundary layer. The characteristics of hypersonic boundary layers are dominated by such temperature increases.

- The viscosity increases with temperature, and this by itself will makes the boundary layer thicker;
- because the pressure p is constant in the normal direction through a boundary layer, the increase in temperature T results in a decrease in density: in order to pass the required mass flow through the boundary layer at reduced density, the boundary-layer thickness must be larger.

Both of these phenomena combine to make hypersonic boundary layers grow more rapidly than at slower speeds. ("*Change of shape*")

Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- **High temperature flows**

The vibrational energy of the molecules becomes excited, and this causes the specific heats c_p and c_v. to become functions of temperature.

In turn, the ratio of specific heats, $\gamma = c_p/c_v$ also becomes a function of temperature.

For air. this effect becomes important above a temperature of 800 K.

As the gas temperature is further increased, chemical reactions can occur.

For an equilibrium chemically reacting gas c_p and c_v are functions of both temperature and pressure, and hence γ =f(T, p).

Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- **High temperature flows**

For air at 1 atm pressure, Oxygen dissociation (O_2 -> 2O) begins at about 2000 K, and the molecular oxygen is essentially totally dissociated at 4000 K.

At 4000 K N_2 dissociation (N_2 -> 2N) begins, and is essentially totally dissociated at 9000 K.

Above a temperature of 9000 K, ions arc formed (N -> N^+ + e^-, and O -> O^+ + e^-), and the gas becomes a partially ionized plasma.

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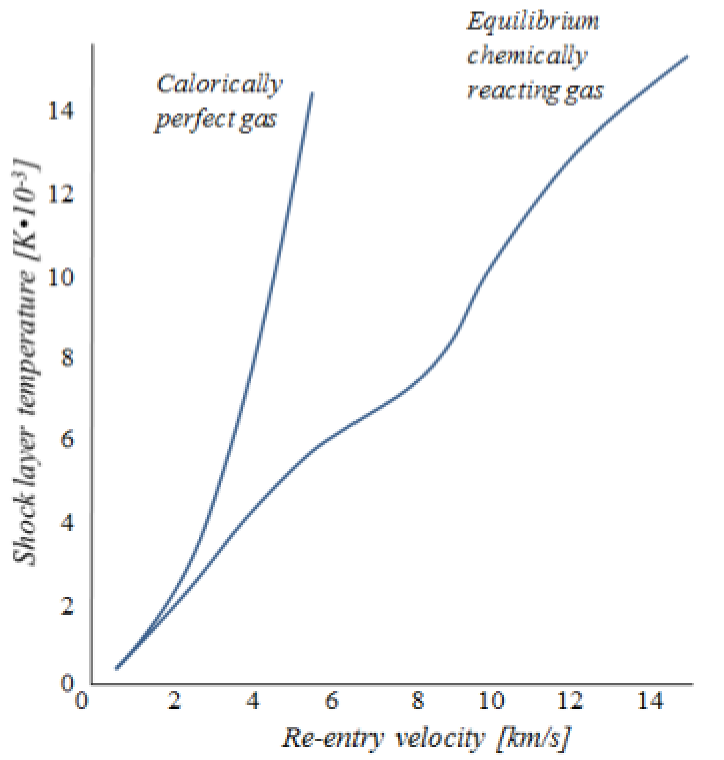
Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- **High temperature flows**

The gas temperature behind the strong shock wave can be enormous at hypersonic speeds.

1. temperature in the nose region of a hypersonic object can be extremely high;
2. The proper inclusion of chemically reacting effects is vital to the calculation of an accurate shock-layer temperature; the assumption that the ratio of specific heats $\gamma = c_p/c_v$ is constant and equal to 1.4 is no longer valid.



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Hypersonic Flows

- **Definition/characterisation of hypersonic flows**

- **High temperature flows**

High-temperature chemically reacting flows can have an influence on aerodynamic characteristics (lift, drag, and moments) on a hypersonic vehicle/object.

For example, such effects have been found to be important to estimate the amount of body-flap deflection necessary to trim the space shuttle during high-speed re-entry.

However, by far the most dominant aspect of high temperatures in hypersonics is the resultant **high heat-transfer rates** to the surface.

Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- **High temperature flows**

This aerodynamic heating takes the form of heat transfer from the hot boundary layer to the cooler surface, called **convective heating**, and denoted by q_c .

Moreover, if the shock-layer temperature is high enough, the thermal radiation emitted by the gas itself can become important, giving rise to a radiative flux to the surface called **radiative heating**, and denoted by q_r

- Example, for Apollo reentry, radiative heat transfer was more than 30 % of the total heating, while
- for a space probe entering the atmosphere of Jupiter, the radiative heating will be more than 95 % of the total heating.

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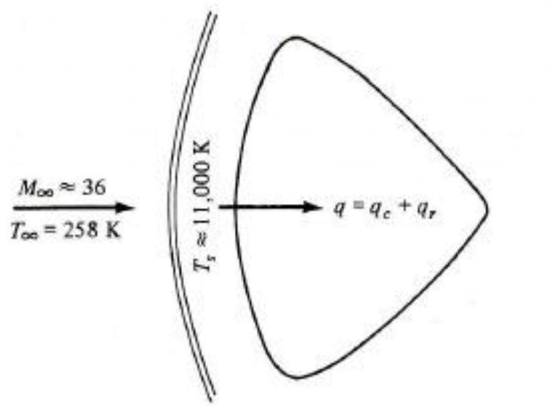
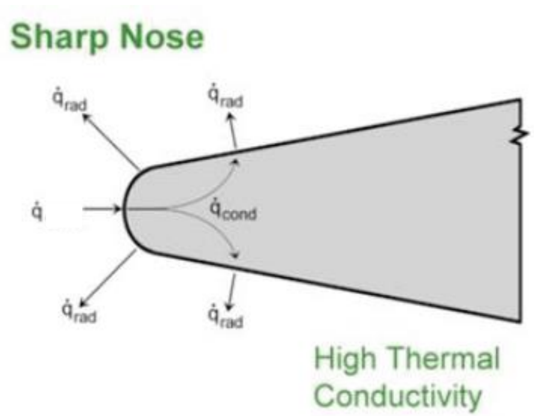
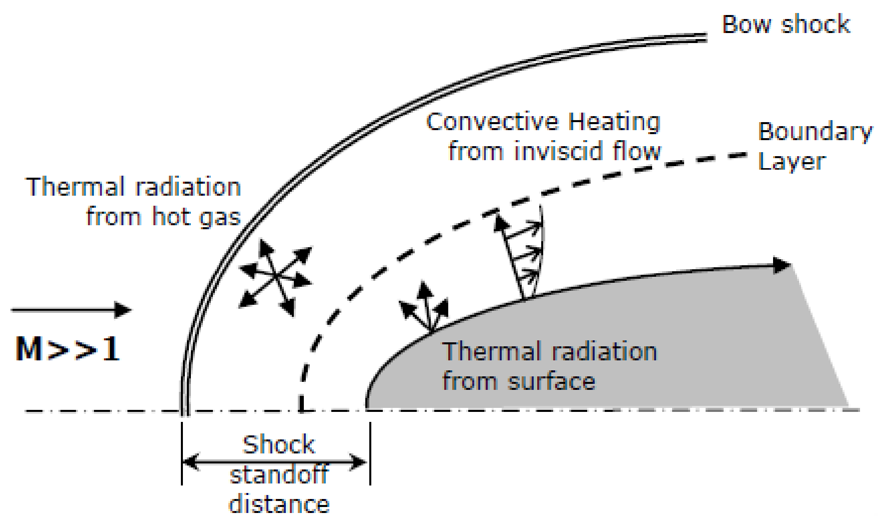
Hypersonic Flows

- **Definition/characterisation of hypersonic flows**
- **High temperature flows**







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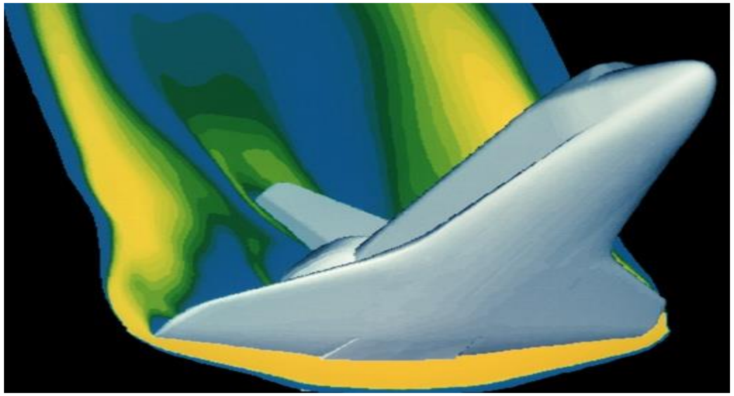
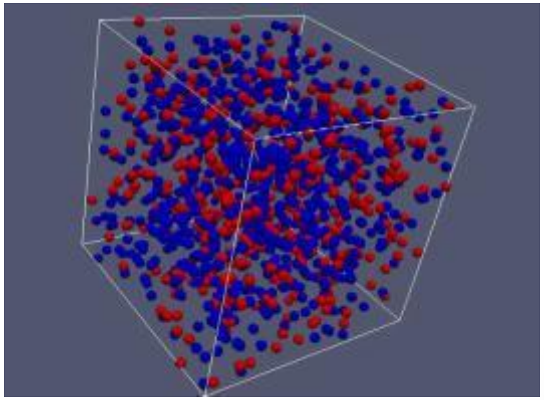
Hypersonic Flows

Aero-thermodynamic characteristics

CFD (Integrated Navier–Stokes equations solutions) for continuum



DSMC (solution to the Boltzmann equation) for molecular regimes

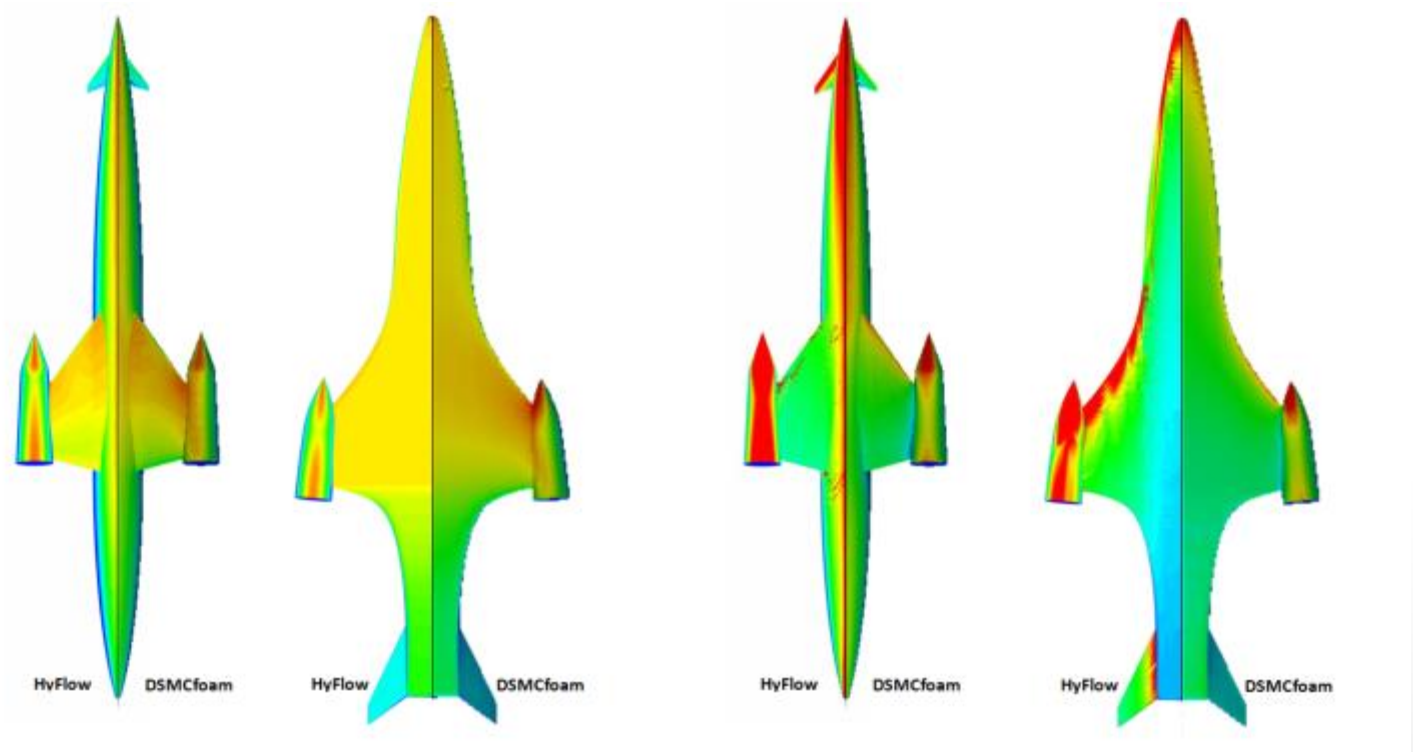


Hypersonic Flows

Aero-thermodynamic characteristics

Pressure distribution

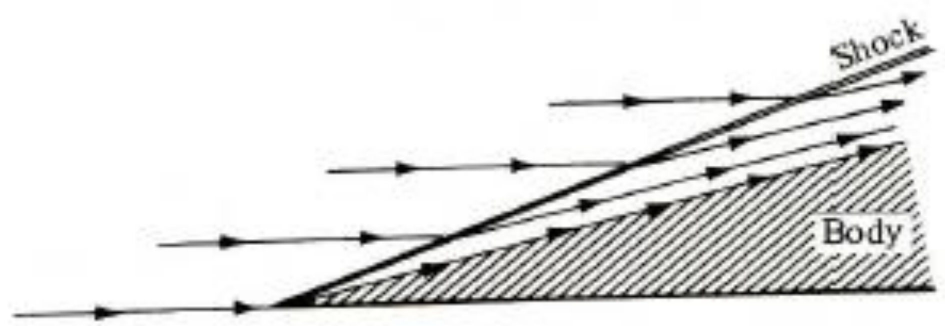
Local heat flux



Wuilbercq et All, 2012

Hypersonic Flows

- **Newtonian Theory for pressure distribution**
- According to newtonian model:
- the flow consists of a large number of individual particles impacting the surface and then moving tangentially to it
- At collision with the surface, the particles lose their component of momentum normal to the surface, but the tangential component is preserved.
- *Force on the surface = time rate of change of the normal component of momentum*

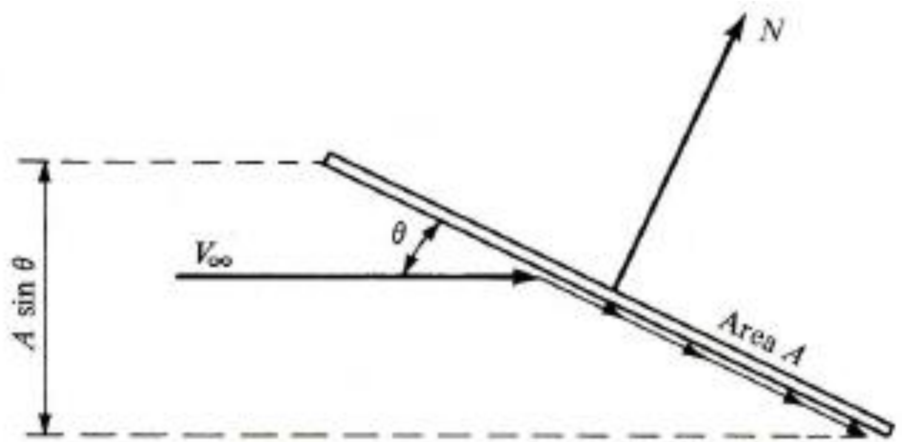


Hypersonic Flows

- **Newtonian Theory for pressure distribution**
- Force on the surface = time rate of change of the normal component of momentum
- Time rate of change of momentum (normal component) is:

$$(\rho_\infty V_\infty A \sin\theta)(V_\infty \sin\theta) = \rho_\infty V_\infty^2 A \sin^2\theta$$

- For the 2nd Newton's law $N = \rho_\infty V_\infty^2 A \sin^2\theta$



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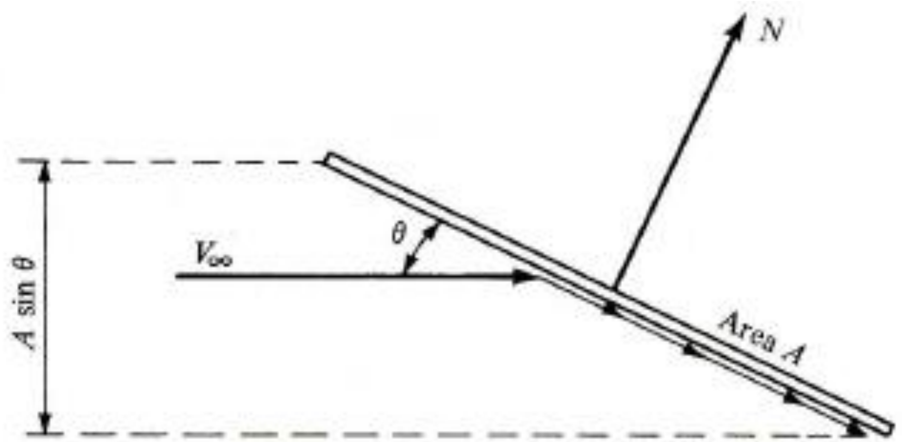
Hypersonic Flows

- **Newtonian Theory for pressure distribution**
- For the 2nd Newton's law $N = \rho_\infty V_\infty^2 A \sin^2\theta$
- Force per unit area $N/A = \rho_\infty V_\infty^2 \sin^2\theta$
- Pressure difference $p - p_\infty = \rho_\infty V_\infty^2 \sin^2\theta$

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2} = 2\sin^2\theta$$



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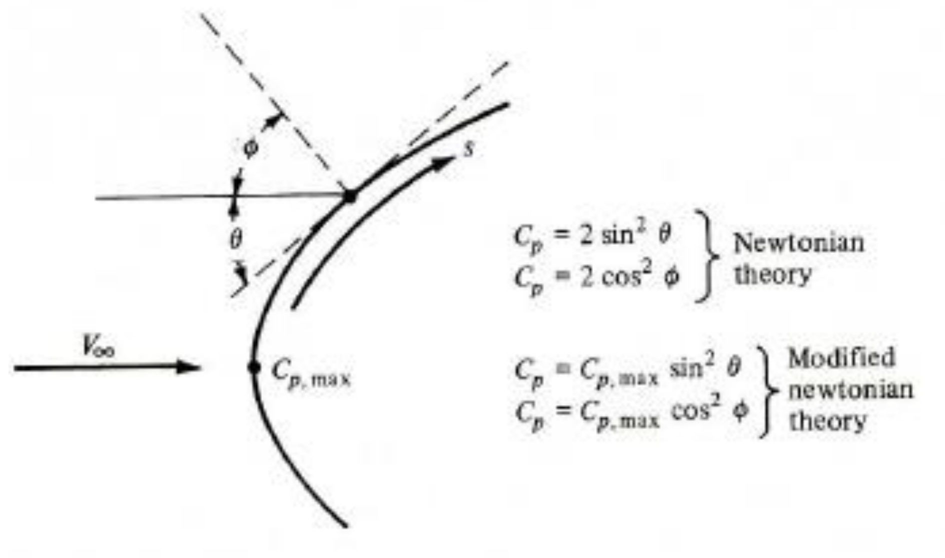
Hypersonic Flows

- **Newtonian Theory for pressure distribution**
- **Modified** newtonian theory (more accurate for calculation of pressure coefficients around blunt bodies)

$$C_p = C_{p,\max} \sin^2 \theta$$



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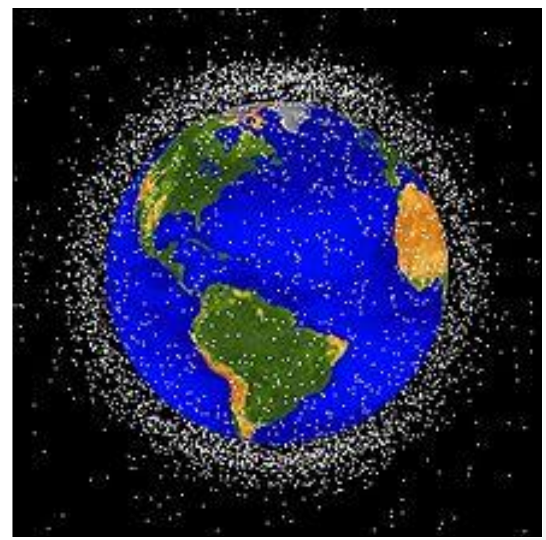
SPACE DEBRIS RE-ENTRY



(C) Wikipedia

Space Debris Re-entry

- The lifetime of objects in low Earth orbits (LEO) is limited due to the atmospheric drag.

- Generally, these objects demise, but surviving fragments of heavy re-entry objects can cause a non-negligible risk to the ground population.

Delta (Photo:NASA)

Space Debris Re-entry

- **Re-entry statistics**
- Since the decay of the Sputnik 1 launch vehicle core stage on December 1957, near 22 000/25 000 catalogued orbiting objects have re-entered the Earth's atmosphere

- More than 5,400 metric tons of materials are believed to have survived re-entry with no major reported casualties

- Largest object to re-enter was the Russian Mir Space Station, which weighed 135,000 kg which was controlled re-entry in the year 2001

- Other large-scale re-entry events were: Skylab (74 tones, July 1979), Salyut-7/Kosmos-1686 (40 tones, February 1991), and Upper Atmosphere Research Satellite (UARS) (5.5 tones, September 2011).

Space Debris Re-entry

- **Re-entry statistics**
- Generally, about 10-40 percent of a satellite's mass will survive re-entry.
- The actual percentage for a specific object depends on the materials used in the object's construction, shape, size, and weight of the re-entering object.

Object recovered from the re-entry of the Delta second stage into Texas was this 250-kg propellant tank (Photo:NASA)

Space Debris Re-entry

- A satellite in circular orbit approaching the re-entry in the atmosphere has a specific mechanical energy of ~3.1 e7 J/kg.
- If all this energy were converted into heat entirely absorbed by the body, most material would be totally vaporized.

Enthalpies of vaporization of common substances, measured at their respective standard boiling points:	
	(J/kg)
Aluminium	10.5 e6
Iron	6.09 e6
Water	2.26 e6

- However, only a small fraction of the energy theoretically available is converted into heat absorbed by the body
- The chance of having surviving satellite components hitting the ground is quite high

Space Debris Re-entry

- Structurally loose components characterized by a high area to mass ratio (e.g. solar panels or large antennae) are generally lost at an altitude around 100 km,
- Most spacecraft and upper stages mainly disintegrate at an altitude of about 78(±10) km, due to the heat and the dynamic loads of the re entry.
- The survivability of specific components depends on a numbers of factors: structure, composition, shape, area to mass ratio, release sequence and shielding from other parts of the system during the *critical phases of maximum heating*.

Space Debris Re-entry

- Surviving fragments of heavy re-entry objects can cause a non-negligible risk to the ground population.
- Space debris mitigation standards specify upper limits for the acceptable risk.

  (NASA-STD-8719.14A)
- Re-entry analysis tools verify the compliance with the applicable standards

Space Debris Re-entry

- **Hazard and risk assessment (*NASA-STD-8719.14A*)**
- Transfer of an orbital environment risk to a potential human casualty risk.
- The potential human casualty risk includes all prompt injuries due to the impact from falling debris as well as exposures to hazardous materials which include chemical, explosive, biological, and radiological materials.
- The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of **15 J** (widely accepted as the minimum level for potential injury to an unprotected person)

Space Debris Re-entry

- **Hazard and risk assessment (*NASA-STD-8719.14A*)**
- For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 ($1:10^4$)
- ESA has also proposed, but not yet officially adopted, a reentry human casualty risk threshold of 1 in 10,000. (2012, to be updated)

Space Debris Re-entry

- **Hazard and risk assessment (*NASA-STD-8719.14A)***

- In order to evaluate the hazard and ground risk due to a single surviving debris, the safety standard introduces an equivalent casualty area D_{Ai} of a single debris, which is composed of the cross-section area A_i of the debris and a projected human risk cross-section area of A_h=0.36 m^2,

$$D_{Ai} = \left(\sqrt{A_h} + \sqrt{A_i}\right)^2$$

- The total casualty area A_c of a reentry event is the summation over all surviving fragments,

$$D_A = \sum_{i=1}^{n} \left(\sqrt{A_h} + \sqrt{A_i}\right)^2$$

Space Debris Re-entry

- **Hazard and risk assessment**

- **Total human casualty expectation, E, can then be defined as**

$$E = D_A \ x \ P_D$$

- where P_D is equal to the average population density for the particular orbital inclination and year of reentry.

Space Debris Re-entry

- Re-entry analysis tools verify the compliance with the applicable standards
- Some commonly used reentry analysis tools, are:
- NASA's **DAS** (Debris Assessment Software) and **ORSAT** (Object Re-entry Survival Analysis Tool), and
- ESA's re-entry analysis module **SESAM** (Spacecraft Entry Survival Analysis Module) and **SCARAB** (Spacecraft Atmospheric Re-entry and Aerothermal Breakup)

Space Debris Re-entry

- The spacecraft modelling is either based on the complete spacecraft structure or on a set of separate objects.

- The re-entry trajectory is calculated either with a 6 degrees-of-freedom integration of the equations of motion (including trajectory and attitude motion) or with a 3 degrees-of-freedom integration (assuming a fixed mean attitude).

- Moreover, each tool has different aerodynamic and aero-thermodynamic models, as well as different atmosphere models.

Space Debris Re-entry

- A complete analysis system for spacecraft destruction requires a multi-disciplinary software system in which the various analysis modules continuously exchange the individual results for a stepwise analysis of the spacecraft re-entry and the resulting destruction.

- The destruction analysis of a spacecraft during its re-entry first requires the geometric and physical models of the spacecraft and of its elements.

Space Debris Re-entry

- In order to treat the evolution (destruction) during re-entry the following aspects have to be modelled:

- flight dynamics of the object,
- aerodynamic and aero-thermal loads,
- (dynamic) spacecraft behaviour under the external loads,
- local heating and the resulting melting process (thermal model)
- mechanical loads and the relevant fragmentation/deformation processes,
- fragment tracking till ground impact

Space Debris Re-entry

- **Flight dynamics of the object**
- In general, the trajectory and attitude motion of each object is determined by numerical integration of the 3-6 DOF equations of motion, describing the change of momentum (3DOFs) and angular momentum (additional 3DOFs) of the spacecraft under the action of external forces (3DOFs) and torques (additional 3DOF)

$$\frac{d}{dt}\left(m\vec{V}\right)=\vec{F}_{ext}$$

$$\frac{d}{dt}\left(I\vec{\omega}\right)=\vec{M}_{ext}$$

Space Debris Re-entry

- **Aerodynamic loads**
- Aerodynamic force and torque are the resulting action of pressure and shear stress distribution over the object surface

$$\vec{F}_a = \frac{\rho V^2}{2} \int_S \left(c_P \vec{n} + c_\tau \vec{t} \right) dS$$

$$\vec{M}_a = \frac{\rho V^2}{2} \int_S \left(\vec{r} \times c_P \vec{n} + \vec{r} \times c_\tau \vec{t} \right) dS$$

- $q = \rho V^2/2$ dynamic free stream pressure, $c_P = p/q$ local pressure coeff., $c_\tau = \tau/q$ local shear stress coeff., $\vec{n}$, $\vec{t}$ surface unit normal and tangential vectors on local surface element, dS, $\vec{r}$ the vector distance to the centre of mass.

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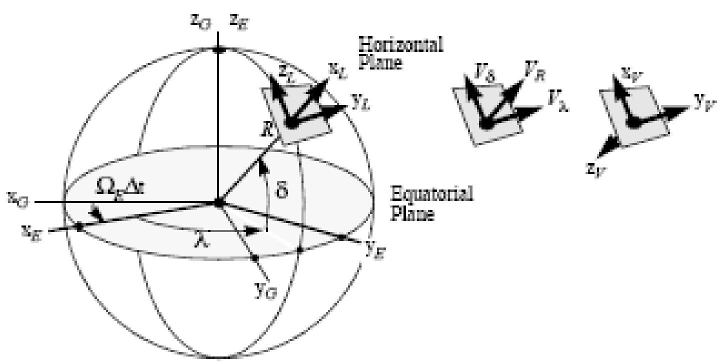
Space Debris Re-entry

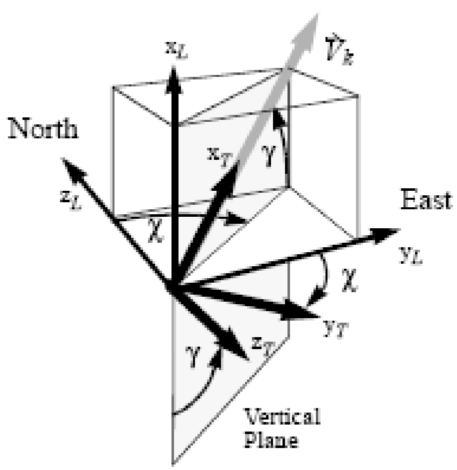
- **Aerodynamic loads**
- Aerodynamic force and torque are the resulting action of pressure and shear stress distribution over the object surface (long. plane)

$$L = \frac{\rho V^2}{2} C_L S \quad ; \quad D = \frac{\rho V^2}{2} C_D S$$

$$M = \frac{\rho V^2}{2} C_M \bar{c} S$$

Space Debris Re-entry





Spherical rotating planet

$$\frac{dr}{dt} = v \sin\gamma$$

$$\frac{d\lambda}{dt} = \frac{v\cos\gamma\sin\chi}{r\cos\delta}$$

$$\frac{d\delta}{dt} = \frac{v\cos\gamma\cos\chi}{r}$$

$$\frac{dv}{dt} = -g\sin\gamma + \frac{-D}{m} + \\ +\omega_E^2 r\cos\delta(\cos\delta\sin\gamma - \sin\delta\cos\gamma\cos\chi)$$

$$\frac{d\chi}{dt} = \frac{v\cos\gamma}{r\cos\delta}\sin\chi\sin\delta + \\ +2\omega_E(\sin\delta - \tan\gamma\cos\delta\cos\chi) + \frac{\omega_E^2 r\cos\delta}{v\cos\gamma}\sin\chi\sin\delta$$

$$\frac{d\gamma}{dt} = -\frac{g}{v}\cos\gamma + \frac{L}{mv} + \frac{v\cos\gamma}{r} + \\ +2\omega_E\sin\chi\cos\delta + \frac{\omega_E^2 r\cos\delta}{v}(\cos\delta\cos\gamma + \sin\gamma\sin\delta\cos\chi)$$

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$$\frac{dV}{dt} = -\frac{\rho S C_D V^2}{2m} - g\sin(\gamma)$$

$$\frac{d\gamma}{dt} = \left(\frac{V}{r} - \frac{g}{V}\right)\cos(\gamma) + \frac{1}{V}\frac{\rho S C_L V^2}{2m}$$

$$\frac{dh}{dt} = V\sin(\gamma)$$

$$\frac{d\theta}{dt} = \frac{V}{r}\cos(\gamma)$$

Spherical **non-rotating** planet

$$\beta_m = \frac{m}{S\,C_D}$$

Ballistic factor

$$\alpha_m = \frac{m}{S\,C_L}$$

Lift factor

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Space Debris Re-entry

- **Aero-thermal loads**
- The aero-thermal analysis predicts the convective heat transfer to the outer surface of the space object based on the aerodynamic and free stream conditions provided by the aerodynamic and flight dynamic calculation, respectively.

- **Mechanical loads and the relevant fragmentation/deformation processes**
- Simplified analysis, restricted to fracture of joints between some elementary parts of the space object..

Space Debris Re-entry

- The available analysis methods can be divided into the following two categories:
- **object-oriented codes,**
- **spacecraft-oriented codes.**

- **Object-oriented methods analyse only individual parts of the spacecraft**.
- These methods usually assume that at a certain altitude the spacecraft is decomposed into its individual elements. For each critical element of the decomposed spacecraft a destructive re-entry analysis is then performed.
- (DAS, ORSAT, SESAM)

Space Debris Re-entry

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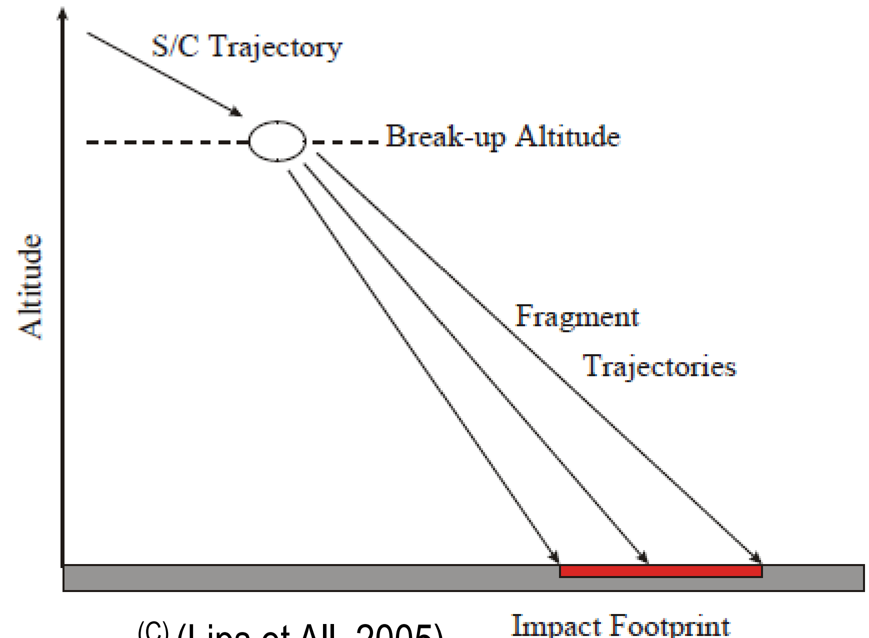
- Aerodynamic and aero-thermodynamic coefficients are calculated for the real, complex geometric shape, and not for simplified object shapes. Breakup events are computed by analysing the actually acting mechanical and thermal loads (i.e. breaking or melting into two more fragments). Shadowing and protection of spacecraft parts by others are taken into account.

Space Debris Re-entry

- **Why Object oriented methods?**
- Object-oriented methods reduce the re-entry analysis of a complete spacecraft to the individual destruction analysis of its critical parts. The concept of a fixed, common breakup altitude usually in the range [75, 85] (km), allows determining a ground impact footprint for the surviving debris objects.

This footprint depends on breakup conditions (position, altitude, velocity vector) and on the ballistic coefficients of the debris objects.



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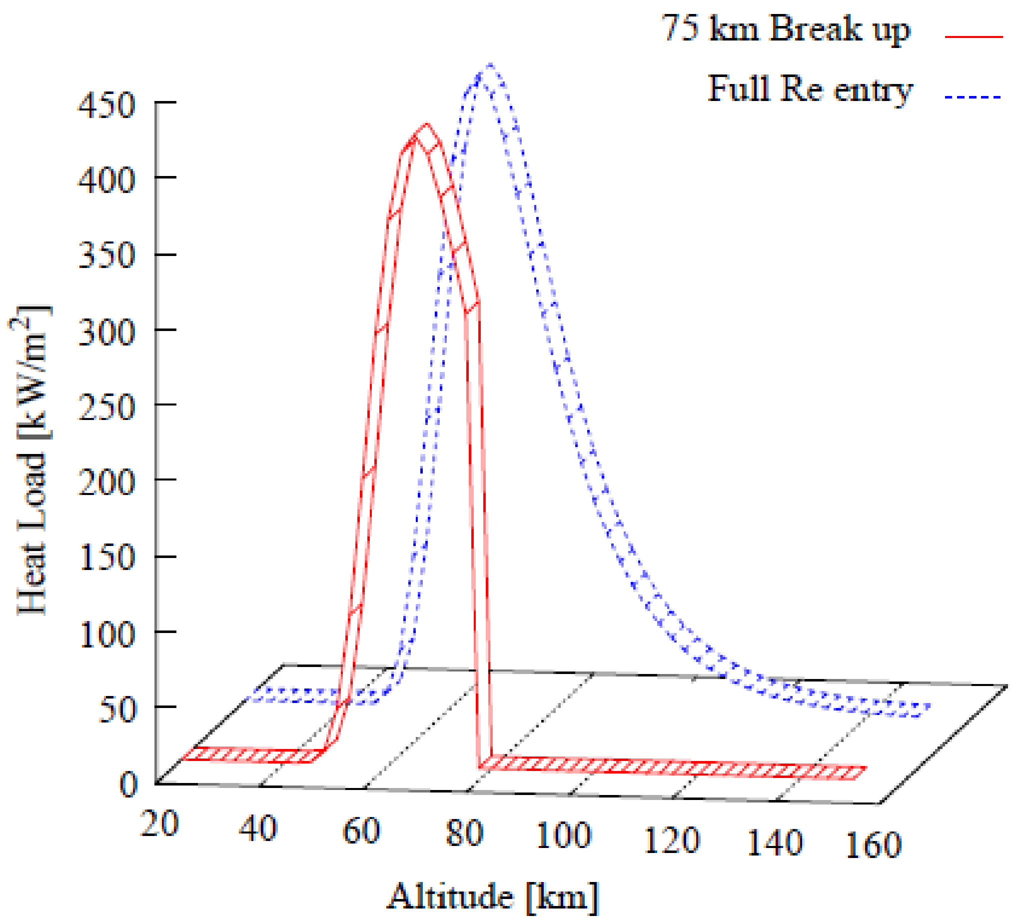
Space Debris Re-entry



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Assumption that the individual destructive re-entry of the spacecraft parts only starts at the breakup altitude, which a priori is unknown => generally prediction of a higher ground risk.

Space Debris Re-entry

- Thus object-oriented codes can (in principle) be used to predict a possible range of the ground risk.

- The minimum ground risk margin is given with high confidence by a full re-entry analysis. The upper margin for the ground risk will strongly depend on the assumed breakup altitude.

- The ground risk will increase with decreasing breakup altitude.

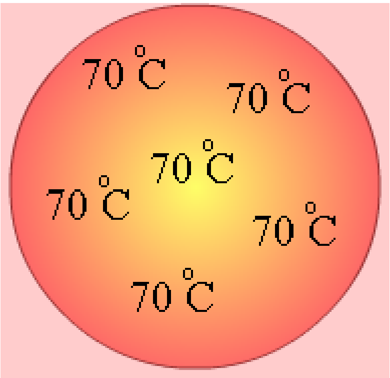
Space Debris Re-entry

- **DAS** (Developed by Lockheed in 1998)
- The spacecraft to be analysed is modelled as a set of geometric objects (spheres, cylinders, boxes, and flat plates).
- Each object is defined by its shape, geometric dimensions, mass, and material.
- For thermal analysis DAS uses a *lumped thermal mass* model for solid objects only.

Space Debris Re-entry

- **DAS**
- For thermal analysis DAS uses a *lumped thermal mass* model for solid objects only.

Temperature variations within the mass can be neglected in comparison with the temperature difference between the mass and the surroundings



- Hollow objects with finite wall thickness or objects consisting of several different materials have to be modelled by an *effective density approach*.
- **Assumption:** an object demises when the accumulated heat input reaches the material heat of ablation (melting)

Space Debris Re-entry

- **DAS**

- Not able to predict partial melting and fragmentation of objects (more conservative approach, i.e. DAS predicts no destruction at all for objects which would be partially molten in reality ... very conservative)

- All material properties in the material database of DAS are assumed to be temperature independent. The emissivity in DAS is constant, 1.0 for all materials.

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Space Debris Re-entry

- **DAS**

- The main output of a re-entry analysis with DAS is a table with the resulting demise altitudes or the calculated casualty areas for each ground impacting object.

- DAS should be used for first risk assessments. If the predicted risk on ground is not acceptable a more accurate tool should be used in order to verify the results of DAS (procedure according to NASA Safety Standard).

Space Debris Re-entry

- **ORSAT** (Developed by the NASA Lyndon B. Johnson Space Center - original version release in 1993)

- Similar to DAS, ORSAT analyses the thermal destruction by melting during a ballistic re-entry for selected shapes of bodies and object motion assumptions.

Object shape	Motion
Sphere	Spinning
	Not spinning
Cylinder	Broadside and spinning
	Random tumbling and spinning
	End-on and spinning
	End-over-end tumbling and spinning
Box	Not tumbling and normal to the flow
	Tumbling
Flat Plate	Not tumbling and normal to the flow
	Tumbling

(Lips and Fritsche, 2005)

Space Debris Re-entry

- **ORSAT**
- It considers thermal heating based on the lumped mass approach or *one-dimensional heat conduction*
- Partial melting of objects is considered by a demise factor.
- Almost all material properties in the material database of ORSAT are temperature dependent.
- Heating by oxidation is considered.

Space Debris Re-entry

- **ORSAT**

- Limited to a ballistic, non-lifting re-entry, then only tumbling motions or stable orientations of the body are allowed

- For boxes, cylinders, plates these are head-on, broadside or normal-to-flow orientations.

- Due to the three-dimensional ballistic flight dynamics model the aerodynamic analysis has to provide only the drag coefficient. The aerodynamic analysis is based on the hypersonic limit *Ma*>>1

Space Debris Re-entry

- **ORSAT**

- A distinction is made between the three flow regimes:
- Hypersonic Free molecular flow $C_{Dfm} = f\,(\text{Shape, Motion})$,
- Hypersonic Rarefied transitional flow $C_{Dtrans} = f\,(\text{Shape, Motion, } Kn)$,
- Hypersonic Continuum flow $C_{Dcont} = f\,(\text{Shape, Motion})$.

- A Knudsen number dependent bridging function is applied in the transitional flow regime:
- $C_{Dtrans} = CDco_{nt} + (C_{Dfm} - C_{Dcont})\left[sin\left(\pi(0.5 + 0.25lgKn)\right)\right]^3$
-

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Space Debris Re-entry

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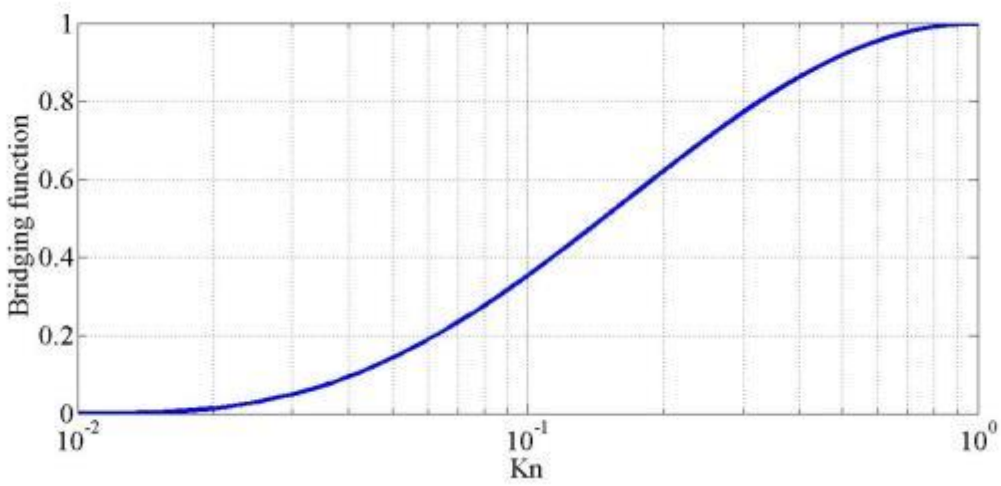
- A Knudsen number dependent bridging function is applied in the transitional flow regime:
- $C_{Dtrans} = C_{Dcont} + (C_{Dfm} - C_{Dcont})\left[sin\left(\pi(0.5 + 0.25lgKn)\right)\right]^3$
- 

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Space Debris Re-entry

- **ORSAT**
- The aero-heating law also distinguishes between the three flow regimes. An averaged shape and motion dependent heat flux to the surface is assumed.
- In hypersonic continuum flow the heat transfer formula for a spherical stagnation point of Detra, Kemp, Riddell is used as the primary basis.
- $\dot{q}_{stcont} = \frac{110\,285}{\sqrt{R_n}} \left(\frac{\rho_\infty}{\rho_{sl}}\right) \left(\frac{V_\infty}{V_{circ}}\right)^{3.15}$ [W m^{-2}] $(V_{circ} \approx 7900 m/s)$
- In free molecular flow:
- $\dot{q}_{stfm} = \frac{\alpha_T \rho_\infty {V_\infty}^3}{2}$ (α_T thermal accommodation coefficient, =0.9)
- Shape-dependent effective radii of curvature and motion-dependent averaging factors are applied in order to use these equations for all object shapes and motion.

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Space Debris Re-entry

- **ORSAT**
- The aero-heating law also distinguishes between the three flow regimes. An averaged shape and motion dependent heat flux to the surface is assumed.

Object shape	Bridging method
Spheres, Cylinders	$0.001 < Kn < 0.01$: Logarithmic Stanton number bridging $0.01 < Kn < 10$: Stanton numbers calculated with Cheng's theory [6] as presented by Cropp [7]
Flat Plates, Boxes	Exponential bridging function: $\dot{q}_{\text{trans}} = \dot{q}_{\text{cont}} \left[1 - \exp\left(-\frac{\dot{q}_{\text{fm}}}{\dot{q}_{\text{cont}}} \right) \right]$

(Lips and Fritsche, 2005)

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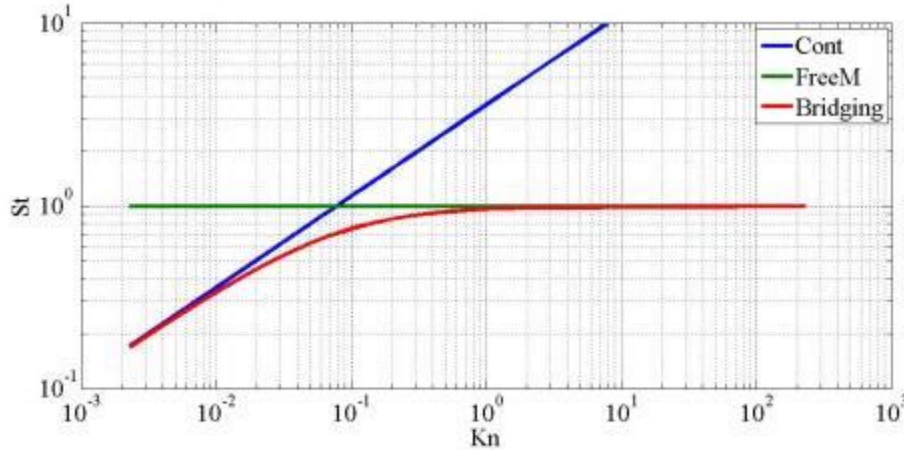
Space Debris Re-entry

- **ORSAT**
- *Stanton number, St* is the ratio of heat transferred to the thermal capacity of fluid

$$St = \frac{\alpha}{\rho V c_p}$$

- where, α = convection heat transfer coefficient, ρ = density of the fluid, c_p = specific heat of the fluid, V = speed of the fluid



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Space Debris Re-entry

- **ORSAT**

- The atmosphere model in ORSAT is the US Standard Atmosphere 1976.

- The Mass Spectrometer Incoherent Scattering Extended-1990 (MSISe-90) model is also available. (There are only small differences between both models in the altitude regime below 120 km.)

Space Debris Re-entry

- **ORSAT**

- ORSAT also provides the possibility to define multiple breakup altitudes and the concept of aerodynamic and thermal mass.

- The aerodynamic mass is used for trajectory calculation whereas the thermal mass is used for the heating analysis. Due to this approach, heavy parent objects (aerodynamic mass) with light weighted shells (thermal mass) can be analysed until the demise of the shells.

- Internal parts can be exposed to the flow subsequently at several calculated breakup altitudes.

Space Debris Re-entry

- **ORSAT**
- Some more recent upgrades of ORSAT include:

- Fay–Riddell heating algorithm with hot gas effects,
- one-dimensional heat conduction in boxes and flat plates,
- radiative heat exchange between an outer object (e.g. housing) enclosing an internal component (e.g. electronic box),
- drag coefficients at low Mach numbers.

Space Debris Re-entry

- **ORSAT**
- Fay–Riddell heating algorithm with hot gas effects,

$$\dot{q}_w = 0.76\,\mathrm{Pr}^{-0.6}(\rho_s\mu_s)^{0.4}(\rho_w\mu_w)^{0.1}\sqrt{\left(\frac{du_e}{dx}\right)_s}$$

$$\times\left[1+\left(Le^{\alpha}-1\right)\frac{h_D}{h_{0\infty}}\right](h_{0\infty}-h_w)$$

- α=0.52 for equilibrium boundary layer (case 1)
- α=0.63 for a frozen boundary layer with fully catalytic wall (case 2)

(Zappardi & Esposito, 2000)

Space Debris Re-entry

- **ORSAT**
- Fay–Riddell heating algorithm with hot gas effects,

$$\dot{q}_w = 0.76\,\mathrm{Pr}^{-0.6}(\rho_s\mu_s)^{0.4}(\rho_w\mu_w)^{0.1}\sqrt{\left(\frac{du_e}{dx}\right)_s}$$

$$\times\left[1+\left(Le^{\alpha}-1\right)\frac{h_D}{h_{0\infty}}\right](h_{0\infty}-h_w)$$

- ρ is the density [kg m^{-3}] ; μ is the viscosity [kg m^{-1} s $^{-1}$] ; u_e is the component of velocity along the body surface; x is the coordinate along the body surface; h_D is the free stream dissociation energy per unit mass [J kg^{-1}]
- subsctipt “s” is “stagnation condition (inviscid)
- *Pr* is the Prandtl number; *Le* is the Lewis number;

(Zappardi & Esposito, 2000)

PUSHING THE BOUNDARIES OF SPACE RESEARCH TO SAVE OUR FUTURE STARDUST

Space Debris Re-entry

- **ORSAT**
- *Pr* is the Prandtl number: ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity

$$\mathrm{Pr} = \frac{\nu}{\alpha}$$

- ($Pr \ll 1$ thermal diffusivity dominates),($Pr \gg 1$ means momentum diffusivity dominates)

- *Le* is the Lewis number: ratio of thermal diffusivity to mass diffusivity

$$Le = \frac{\alpha}{D}$$

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Space Debris Re-entry

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$$\times\left[1-\frac{h_D}{h_{0\infty}}\right](h_{0\infty}-h_w)$$

- for a frozen boundary layer with a non catalytic wall (case 3)

(Zappardi & Esposito, 2000)

Space Debris Re-entry

- Chemical non-equilibrium by Damkohler number, *Da*, which is the ratio between the fluid motion time scale and the chemical reaction time scale:

$$Da = \frac{\tau_f}{\tau_c}$$

- When $Da \rightarrow \infty$ the internal energy relaxation or chemical reaction time scale approaches zero and the gas is in equilibrium. That is its chemical state adjust immediately to changes in the flow.

- When $Da \rightarrow 0$, the reaction time scale approaches infinity, the gas is frozen and does not adjust to changes in the flow.

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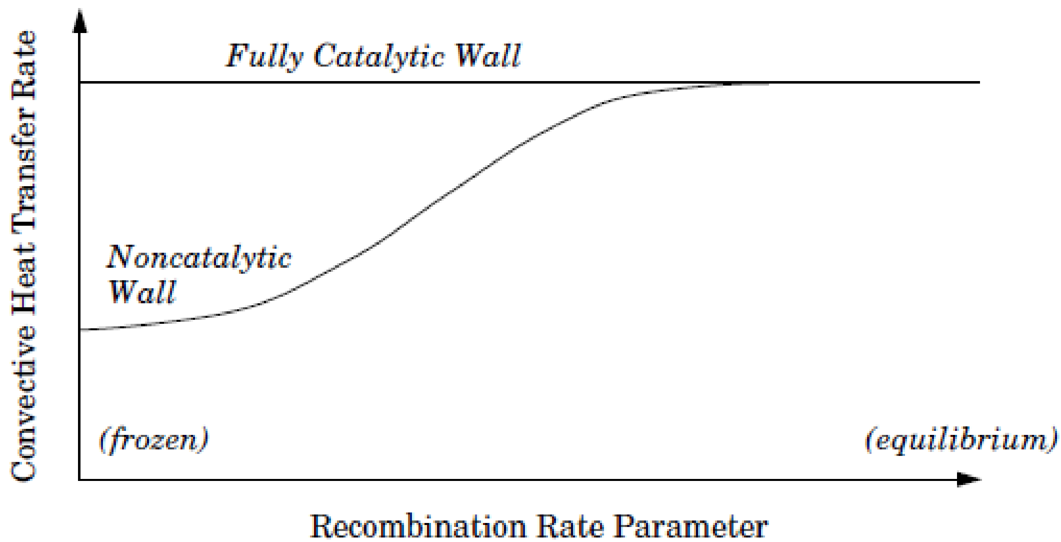
Space Debris Re-entry

- **Finite-rate wall catalysis**
- One of most important parameters that determines the convective heat transfer rate for hypersonic vehicles is the surface catalytic efficiency.



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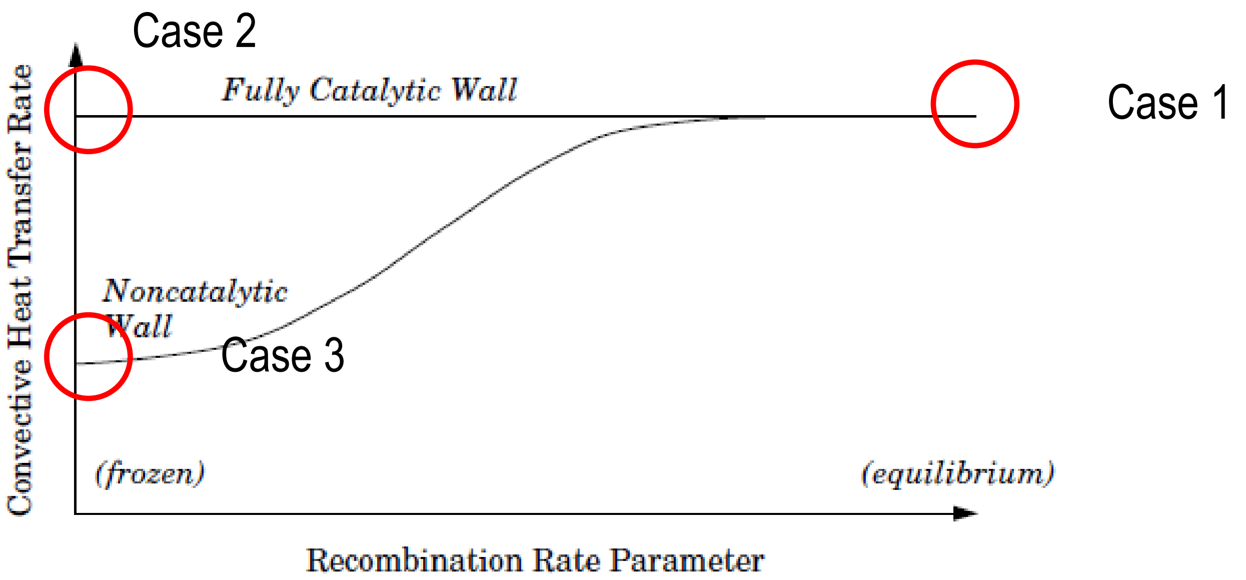

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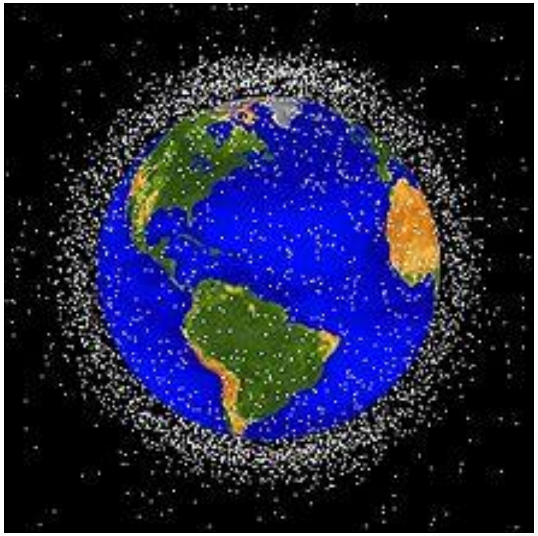
SPACE DEBRIS RE-ENTRY
END 1ST PART



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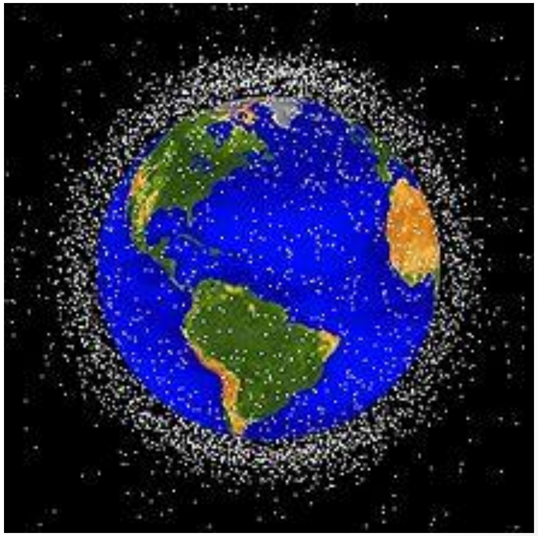
SPACE DEBRIS RE-ENTRY
2^{ST} PART



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Space Debris Re-entry

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Space Debris Re-entry

- **SESAM**

- The main output of the analysis is the mass, cross-section, velocity, incident angle, and impact location of the surviving fragments.

- SESAM is a direct implementation of the aerodynamic and aero-thermodynamic methods used in ORSAT, with some exceptions.

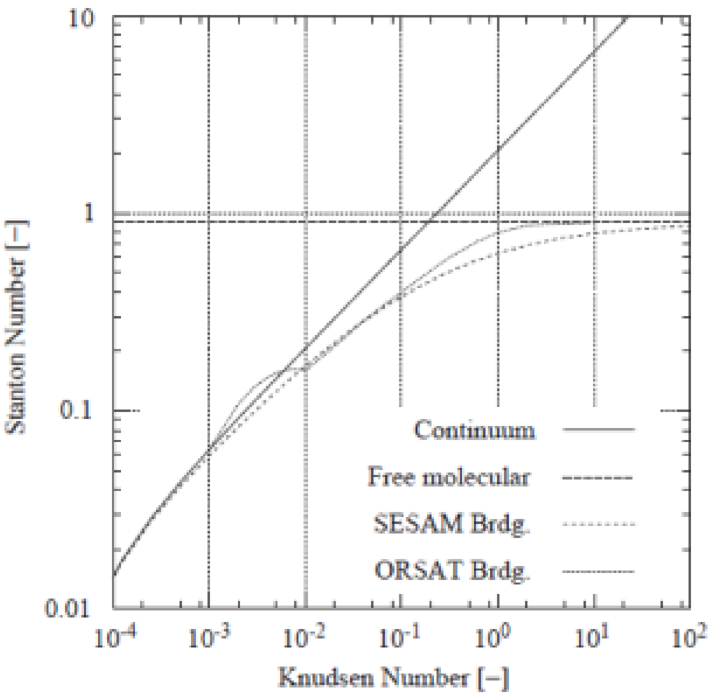
Space Debris Re-entry

- **SESAM**
- Exceptions are:
  - same geometric shapes, only random tumbling or spinning;
  - only lumped thermal mass model, but with continuous melting/mass decrease;
  - temperature-independent material database, no oxidation heating;
  - simplified subsonic drag coefficient for *Ma*<1 (50% of the hypersonic continuum drag coefficient);
  - simplified, steady stagnation point heat flux rate bridging in transitional flow regime

Space Debris Re-entry

- **SESAM**
- simplified, steady stagnation point heat flux rate bridging in transitional flow regime

$$St_{trans} = \frac{St_{cont}}{1 + \frac{St_{cont}}{St_{fm}}}$$



Space Debris Re-entry

- **SCARAB**
- Spacecraft oriented code
- Developed by *Hypersonic Technology Göttingen* (HTG) since 1995 within the frame of several ESA/ESOC contracts
- Aerodynamic and aero-thermodynamic coefficients are calculated for the real, complex geometric shape
- Realistic breakup
- Shadowing

Space Debris Re-entry

- **SCARAB** is a multi-disciplinary analysis tool which incorporates:
- a CAD-like user interface to define the geometry, mass, and material properties of a complex spacecraft,
- a 6 degrees-of-freedom (6 DoF) flight dynamics analysis to predict the trajectory and attitude,
- an aerodynamic analysis to compute perturbing forces and torques,
- an aerothermal analysis to determine heat flux,
- a thermal analysis to determine the heat balance in each part of the spacecraft, and
- a structural analysis to monitor local stress levels.

- A break-up is initiated, if local stress limits are exceeded, or if load-bearing joints are molten.

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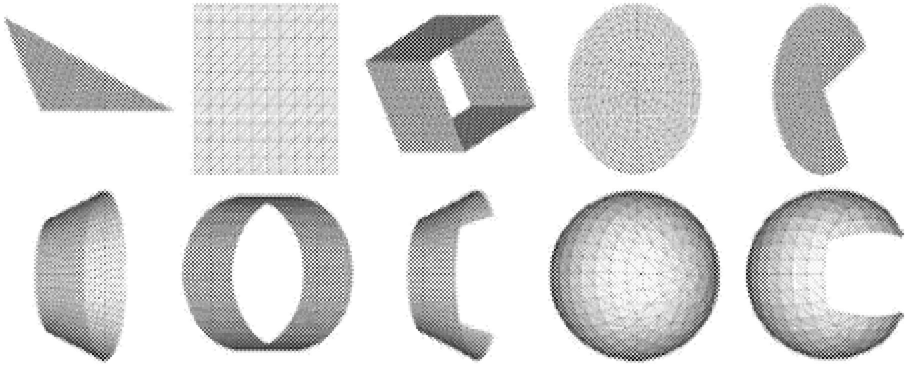
Space Debris Re-entry

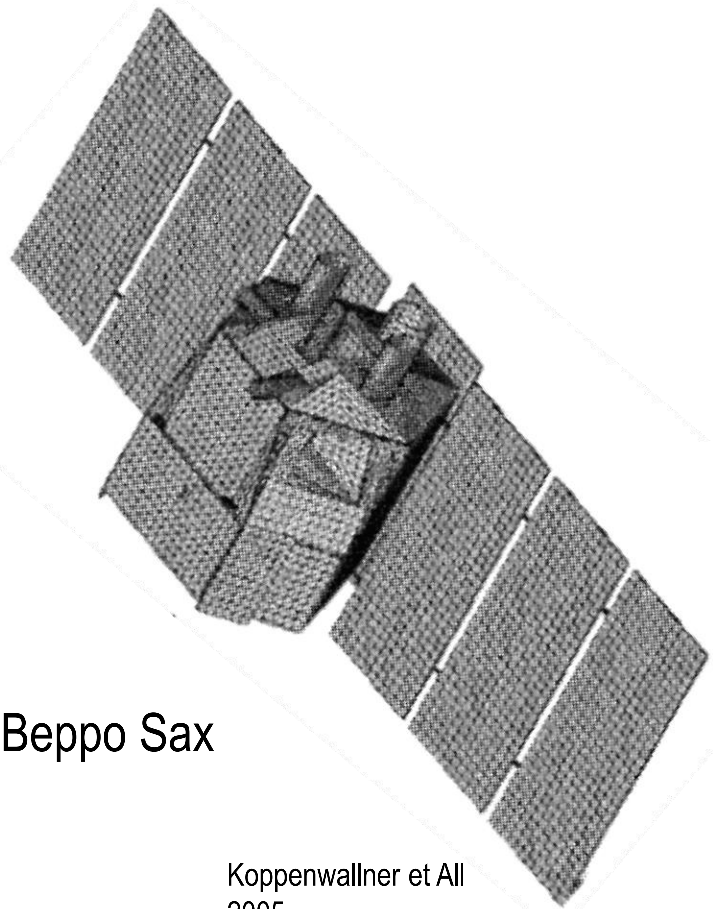
- **SCARAB**
- SCARAB has a graphical modelling system => completely panelised, consistent geometric model of the spacecraft
- hierarchy levels, allowing the composition of complex system by subsystems, compounds, elements and finally primitives (elementary geometric shapes, e.g. spheres, cylinders, boxes) as the lowest level



Koppenwallner et All 2005

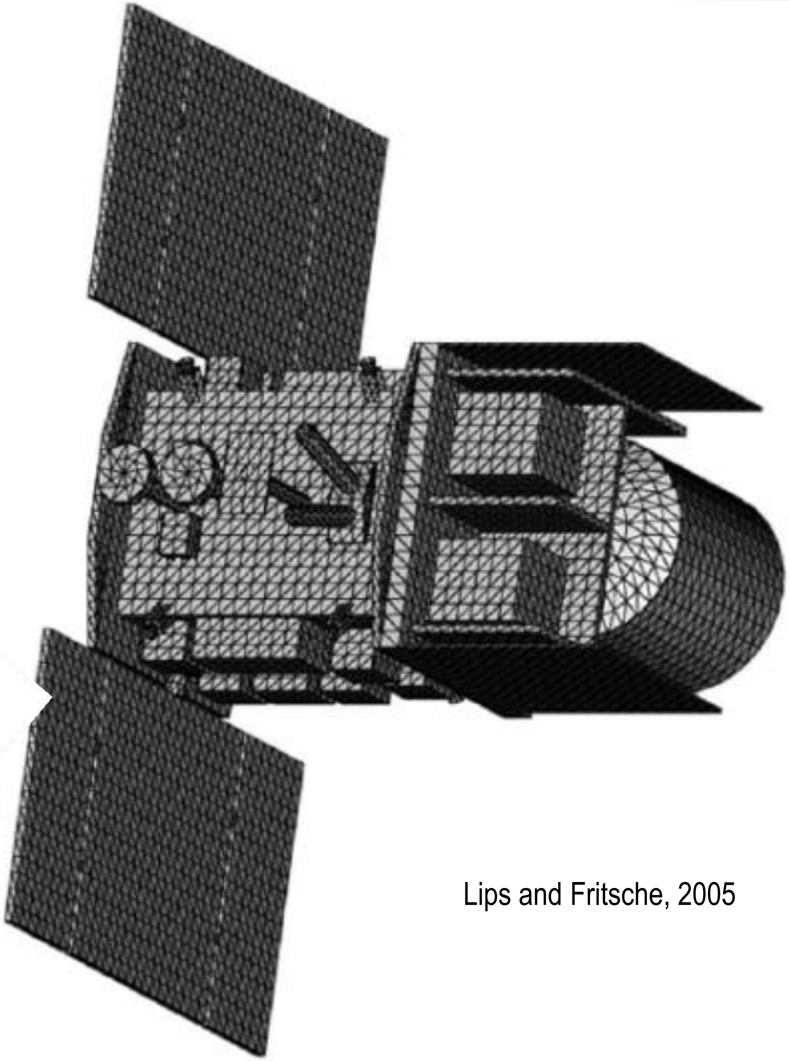
Space Debris Re-entry

- **SCARAB**



Beppo Sax

Koppenwallner et All
2005



Lips and Fritsche, 2005

Space Debris Re-entry

- **SCARAB**

- The material database contains about 20 physical properties:
  - temperature independent like density, melting temperature, and heat of melting.
  - temperature-dependent like ultimate tensile strength, elasticity module, specific heat capacity, thermal conductivity, and emission coefficient.

- From “monolithic, solid, metallic, and isotropic materials “ to also “liquid or gaseous tank contents, non-metallic ceramics, glasses or plastics, and orthotropic, multi-layered composites (e.g. honeycombs, fibre reinforced plastics)”

Space Debris Re-entry

- **SCARAB**
- Liquid and gaseous tank contents modelled as virtual solids by using available material properties.
- Tank contents are assumed as fixed and do not slosh around in the tank.
- Melting temperature set very high to ensure no melting.
- Density from the volume of the tank and the mass of the content. (assumed constant until a possible tank bursting).
- Strength and elasticity are both zero, because a virtual solid cannot take any forces.
- Heat capacity and thermal conductivity determined for the mean operating pressure of the tank.

Space Debris Re-entry

- **SCARAB**
- non-metallic materials difficult to treat because of their completely different destruction process at high temperatures
  - Crystalline ceramics can be treated as metallic materials, but their melting point depends on atmospheric conditions.
  - Semi-crystalline glass ceramics and amorphous glasses: no exact melting point can be defined

Space Debris Re-entry

- **SCARAB**
- Problematic materials: plastics (also in composite form like carbon fibre reinforced plastic, CFRP).
- do not melt at high temperatures, but destroyed in a combination of sublimation, oxidation, and other types of chemical reactions or decompositions at molecular level
- equivalent resistance against thermal destruction has to be defined by adapting melting temperature, heat of melting, heat capacity, thermal conductivity and emission coefficient.

Space Debris Re-entry

- **SCARAB**
- Model orthotropic properties
- Honeycomb composites can be modelled, as long as the honeycomb core and the sheet panels consist of the same material. In this case, they can be modelled as a monolithic material with reduced density and thermal conductivity
- Each layer of the composites can also be modelled separately using different materials

Space Debris Re-entry

- **SCARAB**
- a spacecraft is composed of a large number of elementary geometric shapes, each with uniform material properties.
- All elementary shapes are discretized into volume elements (voxels) with planar surface facets which are adjacent to a neighbouring voxel, or form a part of the outside or inside surface of the spacecraft.

Space Debris Re-entry

- **SCARAB**
- At every other integration step the mass properties are re-evaluated, and the aerodynamic, aero-thermal, and thermal view factors of each voxel are re-determined to account for attitude changes, break-ups, or melting.
- The perturbing aerodynamic forces and moments (translational and rotational accelerations) are determined by a surface integral over all voxel surfaces which are exposed to the flow field of density ρ and aerodynamic velocity V_∞.

Space Debris Re-entry

- **SCARAB**
- Hypersonic approximations are used for the aerodynamic model (three flow regimes).

Aerodynamic and aerothermodynamic model of SCARAB

Flow regime	Aerodynamic model	Aerothermodynamic model
Free molecular flow	Free molecular integral method with Nocilla or Schaaf–Chambre accommodation coefficients; no catalysis or chemical reactions (inert wall)	
Transition regime	Knudsen number and local flow inclination dependent bridging	General bridging formula: $\dot{q} = \dfrac{\dot{q}_{\mathrm{cont}}}{\sqrt{1 + (\dot{q}_{\mathrm{cont}}/\dot{q}_{\mathrm{fm}})^2}}$
Continuumflow	Modified Newtonian theory (function of Mach number, specific heat ratio, and local flow inclination)	Modified Lees theory: [16,14] $St = \dfrac{2.1}{\sqrt{Re_{\infty,0}}}(0.1 + 0.9\cos\Theta)$ Assumed viscosity law: $\mu(T) \propto T^{0.78}$

(Lips and Fritsche, 2005)

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Space Debris Re-entry

- **SCARAB**

- Free molecular flow:

$$c_{p,fm} = \frac{\sigma_N}{\sqrt{\pi} S_\infty^2} \left[\frac{2-\sigma_N}{\sigma_N} \Pi(S_n) + \frac{1}{2} \sqrt{\frac{T_w}{T_\infty}} \chi(S_n) \right]$$

$$c_{\tau,fm} = \frac{\sigma_\tau}{\sqrt{\pi} S_\infty^2} \sin(\theta) \chi(S_n)$$

- $S_\infty = {}^{V_\infty}/_{\sqrt{2RT_\infty}}$, is the free-stream molecular speed ratio
  $S_n = S_\infty \cos(\theta)$ is its normal component to an inclined surface element, Π and χ are some functions of S_n., and T_∞ is free stream the temperature, let T_w and θ are the local wall temperature and incidence angle

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Space Debris Re-entry

- **SCARAB**

Schaaf and Chambre accommodation coefficients, σ_N and σ_τ accommodate the incident and refected energies.

- Free molecular flow:

$$c_{p,fm} = \frac{\sigma_N}{\sqrt{\pi} S_\infty^2} \left[\frac{2-\sigma_N}{\sigma_N} \Pi(S_n) + \frac{1}{2} \sqrt{\frac{T_w}{T_\infty}} \chi(S_n) \right]$$

$$c_{\tau,fm} = \frac{\sigma_\tau}{\sqrt{\pi} S_\infty^2} \sin(\theta) \chi(S_n)$$

- $S_\infty = {}^{V\infty}/_{\sqrt{2RT\infty}}$, is the free-stream molecular speed ratio
  $S_n = S_\infty cos(\theta)$ is its normal component to an inclined surface element, Π and χ are some functions of S_n., and T_∞ is free stream the temperature, let T_w and θ are the local wall temperature and incidence angle

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Space Debris Re-entry

- **SCARAB**

- Hypersonic continuum flow
- Modified Newtonian approach
- For wetted surfaces ($\theta < \pi/2$)

$$c_{p,cont} = k_{N1}(\gamma, M_\infty, \theta)\cos^2(\theta) + k_{N2}(\gamma, M_\infty, \theta)$$
$$c_{\tau,cont} = 0$$

- γ is the specific heats ratio

Space Debris Re-entry

- In particular the local pressure and shear stress coefficients c_p and c_τ can be determined for each of the re-entry flow regimes according to:
- Transition by bridging

$$c_{p,trans} = c_{p,cont} + \left(c_{p,fm} - c_{p,cont}\right) f_p\left(Kn_{\infty,s}\right)$$
$$c_{\tau,trans} = c_{\tau,cont} + \left(c_{\tau,fm} - c_{\tau,cont}\right) f_\tau\left(Kn_{\infty,s}\right)$$

- $Kn_{\infty,s}$ is based on free stream density and stagnation point temperature and viscosity.

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Space Debris Re-entry

- **SCARAB**
- These models are applied locally to the panels of the geometric model.
- Integral force and torque coefficients are calculated from the resulting pressure and shear stress distribution over the spacecraft surface.

- The aero-thermal analysis predicts the convective heat transfer to the outer surface of the spacecraft based on the aerodynamic conditions.
- Like the aerodynamic coefficients, the heat transfer is computed as a combination of the free molecular and continuum values

Space Debris Re-entry

- **SCARAB**

$$St = \frac{\alpha}{\rho V c_p} = \frac{\dot{q}}{\rho V c_p \Delta T}$$

- Free molecular heating
- "Stanton number computed with standard approach equivalent to pressure and shear stress coeff.

$$St_{fm,s} \approx 1$$

- Continuum $$St_{cont} = \frac{2.1}{\sqrt{\mathrm{Re}_{\infty,s}}}(0.1 + 0.9\cos\theta)$$

$$\mathrm{Re}_{\infty,s} = \frac{\rho_\infty V_\infty R_N}{\mu(T_s)}$$

Power law viscosity dependence on temperature

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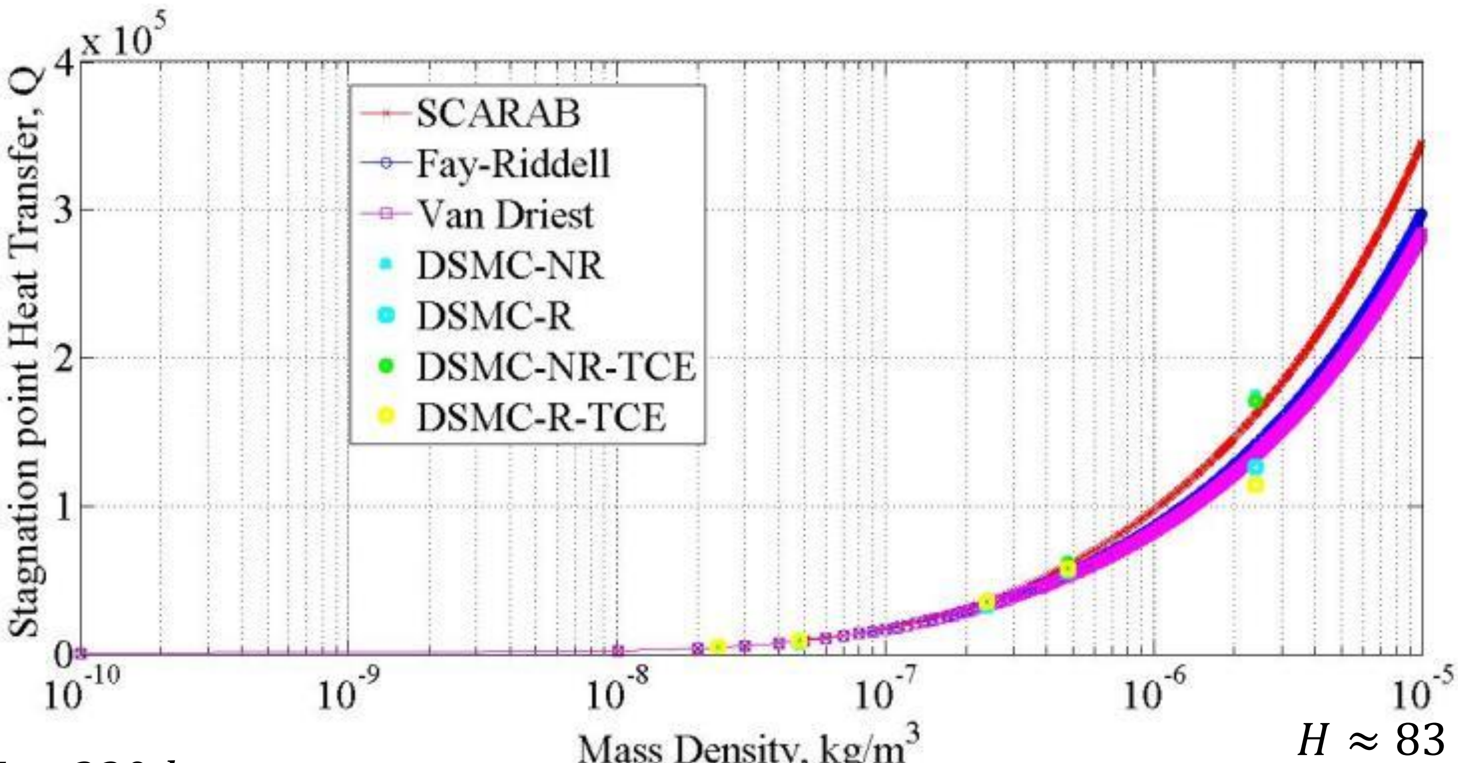
Space Debris Re-entry

- **SCARAB**



$H \approx 230\ km$

$H \approx 83\ km$

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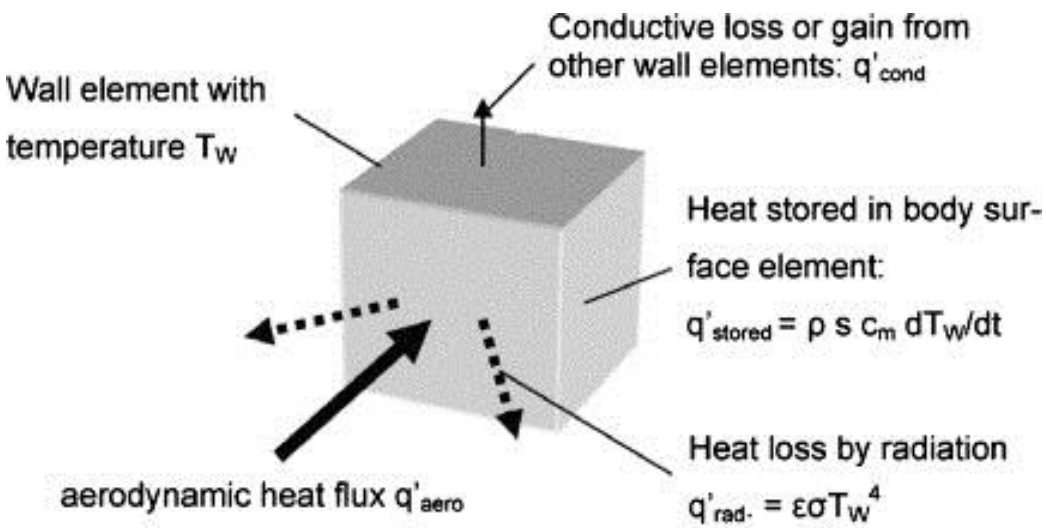
Space Debris Re-entry

- **SCARAB**
- The thermal analysis is based on a two-dimensional heat conduction model (radial or lateral neighbouring panels).

Destruction by melting is analysed on panel level.



Heat flux balance for wall element of body

Space Debris Re-entry

- **SCARAB**
- Angle of attack and bank angle variation (constant lift-to-drag ratios) is used for *Ma*<6 within the supersonic, transonic, and subsonic regime to calculate the ground dispersion of the surviving fragments.

- Several atmosphere models are available, including US Standard 1976, MSISe-90, MSISe-00, Jacchia-71

Space Debris Re-entry

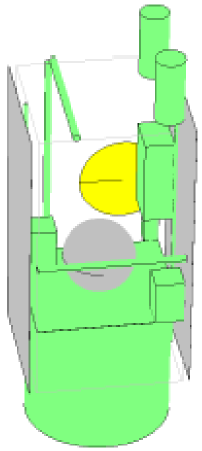
- COMPARISON of ORSAT and SCARAB Reentry Analysis Tools for a Generic Satellite Test Case (extracted from Kelley et All, Bremen, 2010)

- **NASA ORSAT**
  - "Object-oriented" model
    - ➢ Reentering spacecraft are modeled as a set of simplified geometric shapes
      - Spheres
      - Cylinders
      - Boxes
      - Flat Plates
  - 3 degrees-of-freedom equations of motion
    - ➢ Stable attitude
    - ➢ No assumed lift
  - Aerodynamic and aerothermodynamic models based on shape, motion and Knudsen number dependant functions for drag and heating
  - Thermal analysis with a 1-D heat conduction model
  - Assumed break-up altitude of 78 km

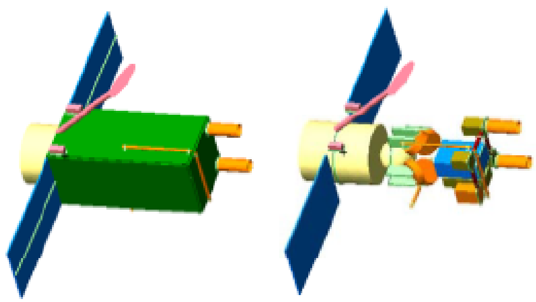
- **ESA SCARAB**
  - "Spacecraft-oriented" model
    - ➢ Reentering spacecraft modeled as close to real geometry as possible using triangular panelized surfaces
  - 6 degrees-of-freedom equations of motion
    - ➢ Integration of attitude motion
  - Aerodynamic and aerothermodynamic models based on local panel methods
  - Thermal analysis with 2-D heat conduction model
  - Break-up model based on stress and structural integrity checks

Space Debris Re-entry

- COMPARISON of ORSAT and SCARAB Reentry Analysis Tools for a Generic Satellite Test Case (extracted from Kelley et All, Bremen, 2010)



Early generic satellite concept sketch by ORSAT Team



SCARAB model for generic satellite

- **Joint Development between ORSAT Team at JSC and the SCARAB Team at HTG**
  - 35 unique objects representing simplified models of typical satellite components
  - Approximately 400 kg mass
    - ORSAT – 391.641 kg
    - SCARAB – 401.531 kg
    - Difference +9.89 kg (+2.53% w.r.t. ORSAT mass)
    - Differences result from 3 primary effects
      - SCARAB requires all connection elements to be modeled
      - Material densities are slightly different
      - Masses in SCARAB are calculated based on the mass of the triangular panels each object is comprised of
  - Initial trajectory conditions
    - Altitude – 122 km
    - Velocity – 7.41 km/s
    - Inclination – 52°
    - Flight Path Angle – -0.1°
  - Environmental Conditions
    - Zonal Harmonics up to J4
    - Earth Flattening
      - Eccentricity of Earth = 0.08182
    - U.S. Standard 1976 Atmosphere

Space Debris Re-entry

- COMPARISON of ORSAT and SCARAB Reentry Analysis Tools for a Generic Satellite Test Case (extracted from Kelley et All, Bremen, 2010)

- **ORSAT**
  - 21 Surviving components representing a mass of 47.22 kg (12.1%) DCA = 15.377 m^2
    - Debris footprint begins at 678 km (LH2 Tank) and ends at 849 km (Command Box)
      - Footprint Length = 171 km
- **SCARAB**
  - 6 Surviving components representing a mass of 40.91 kg (10.19%) DCA = 4.428 m^2
    - Debris footprint begins at 744.53 km (LH2 Tank) and ends at 1013.1 km (Battery Box Contents)
      - Footprint Length = 268.7 km
- **Differences**
  - Compared to SCARAB, ORSAT Predicts:
    - 15 more surviving objects
    - 6.31 kg more surviving mass
    - A DCA 10.949 m^2 higher
    - A Footprint 97.57 km shorter beginning 66.53 km sooner
- **Surviving fragments can be divided into 3 areas for study**
  1. Objects which survive in both codes
     - There are five of these objects; LH2 Tank and (4) RWA Flywheels
  2. Objects which only survive in one code
     - Command box survives only in ORSAT
  3. Objects which survive differently
     - The Battery Cells and Battery Box Frames survive in both codes, but in different ways

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Space Debris Re-entry

- COMPARISON of ORSAT and SCARAB Reentry Analysis Tools for a Generic Satellite Test Case (extracted from Kelley et All, Bremen, 2010)

- **Looking back at the final results**

	ORSAT			SCARAB	
	Reported Values	Assuming Battery Box Remains Intact	Ignoring Command Box	Reported Values	Using Maximum Area
Surviving Mass (kg)	47.220	**47.220**	43.330	40.91	**40.91**
DCA (m^2)	15.377	**6.033**	5.342	4.428	**5.226**

– By adjusting some of the methods and assumptions in each code the comparison becomes more clear and results begin to converge

- Adjust ORSAT results to account for the fused battery cell and inner frame as in SCARAB
  - ➢ Reduces ORSAT DCA by 9.344 m^2
- Adjust SCARAB cross-sectional area calculation to match those in ORSAT
  - ➢ Use maximum area for RWA Flywheels
  - ➢ Use 0.5*((L*D)+(L*H)) for Battery Box contents
  - ➢ Increases DCA by 0.797
- The end result is that the DCA's between the codes differ by 0.116 m^2 (2.12% w.r.t. ORSAT) when considering only objects surviving in both codes
  - ➢ Difference is 0.807 m^2 (13.37%) when the command box is included

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Space Debris Re-entry

- COMPARISON of ORSAT and SCARAB Reentry Analysis Tools for a Generic Satellite Test Case (extracted from Kelley et All, Bremen, 2010)

  - **Careful examination reveals that ORSAT and SCARAB arrive at very similar results**
    - Of 33 unique objects modeled both codes strongly agree on 31 of those
      - Predict 29 to demise in a similar fashion
      - Predict 2 (LH2 tank, RWA flywheels) to demise in much the same way
    - Only 2 objects (as modeled in SCARAB) show significant variance
      - For the command box ORSAT's prediction of a high demise factor were very close to the results predicted by SCARAB, and may have demised in ORSAT after evaluating the oxidation effects
  - **The large difference in the debris casualty area which resulted form the battery box contents (1 item in SCARAB, 3 unique items in ORSAT) are not an effect of the differing methods employed to model the reentry physics, but are instead a difference in safety philosophy associated with geometric description of components**
  - **It is not possible to deem either method as "correct" or better**
    - Either scenario is equally plausable

Space Debris Re-entry

- **DEBRISK, a Tool for Re-Entry Risk Analysis**
- Developed by CNES from 2008
- Object based approach
- Similar to ORSAT

- **DEBRIS**
- within the DEIMOS Planetary Entry Toolbox
- estimates the footprint on ground of the debris of an uncontrolled re-entry object
- give a first shot of the impact area of the debris produced by a vehicle break-up during its atmospheric entry, exploring also the survivability of the elements

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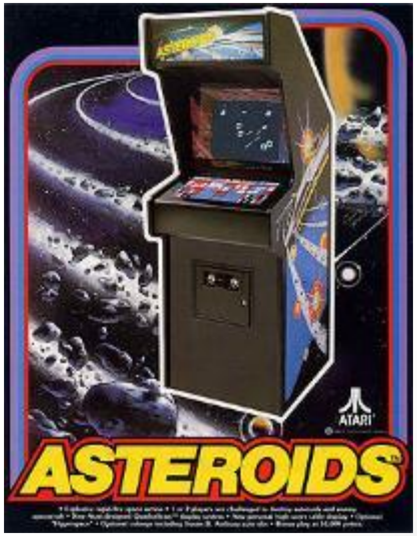
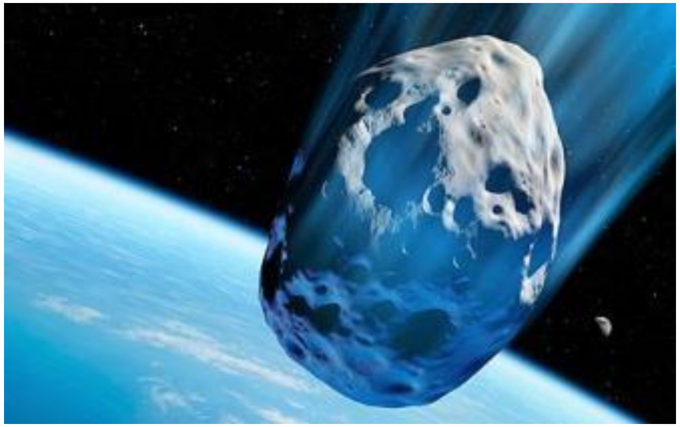


ASTEROID ENTRY

Asteroid Entry

- Complex and coupled physical phenomena such as hypersonic aerodynamics, heating, ablation, fragmentation, fragments interaction, and airburst.
- Asteroid are characterised by very high kinetic energy levels.



Asteroid Entry

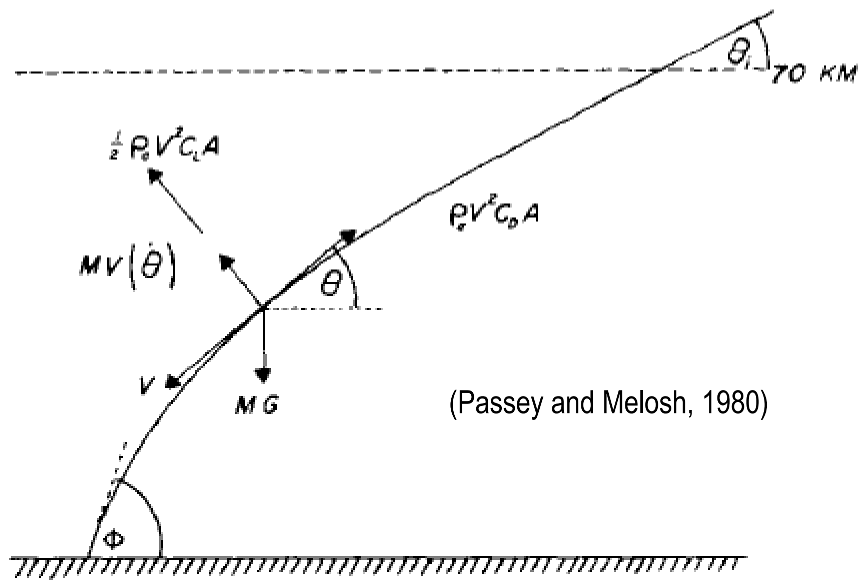
- The strength is defined by impactor composition and structure and varies with meteoroid size [Weibull, 1951].
- In general, the falling body (or each of its fragment) is not homogeneous, and the fragmentation occurs near the "weak" points (cracks or other defects).
- Each fragmentation leads to a decrease in the defect number and an increase in the sub-fragment strength.

Asteroid Entry

- Several differences between the planetary entry of space debris and of asteroids:
  - object properties and entry conditions not known/partially known, with high level of uncertainty.
  - approaches to predict the thermal loads must be different due to much higher velocities involved (up to 70 km/s);
  - the mechanism of the fragmentation is quite different, (more due to mechanical loads than thermal ones for asteroids)

Asteroid Entry

- The fall of a meteorite begins when it enters the upper atmosphere. Its initial geocentric velocity can range from l l.2 to about 70 km sec -1 assuming the meteoroid to be in a heliocentric orbit.
- Its entry angle can also range from near 0 to 90 [deg] with respect to the local horizont, with 45 [deg] being the most likely entry angle



(Passey and Melosh, 1980)

Asteroid Entry

- As the meteoroid collides with atoms in the air, some of its kinetic energy is dissipated.
- Some of this energy is used in ablating the body by melting and/or vaporizing the exposed surface.
- Some of its momentum is also transferred to the air and the resultant atmospheric drag decelerates the meteoroid.

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Asteroid Entry

- There are two fundamentally different approaches to the description of the motion of a fragmented meteoroid.
- In the first one the impactor is considered to be a strength-less liquid like object or drop (hydrodynamic approximation).
- Many simplified semi-analytical models have been developed to describe the deformation (a change of cross section) and deceleration of this drop [Grigorian, 1979; Hills and Goda, 1993; Chyba et al., 1993; Crawford, 1997].

Asteroid Entry

- The second approach is based on studying the motion of a finite number of large fragments, which interact with each other through the air pressure.
- The direct observations and the crater fields on the Earth's surface support the view that at least some falling bodies undergo fragmentation into several large pieces that move a long distance without further disruption.
- If the number of fragments is not great enough, they cannot be described in the frame of continuous medium approximation.

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Asteroid Entry

Atmospheric entry can be described by simplified differential equations for

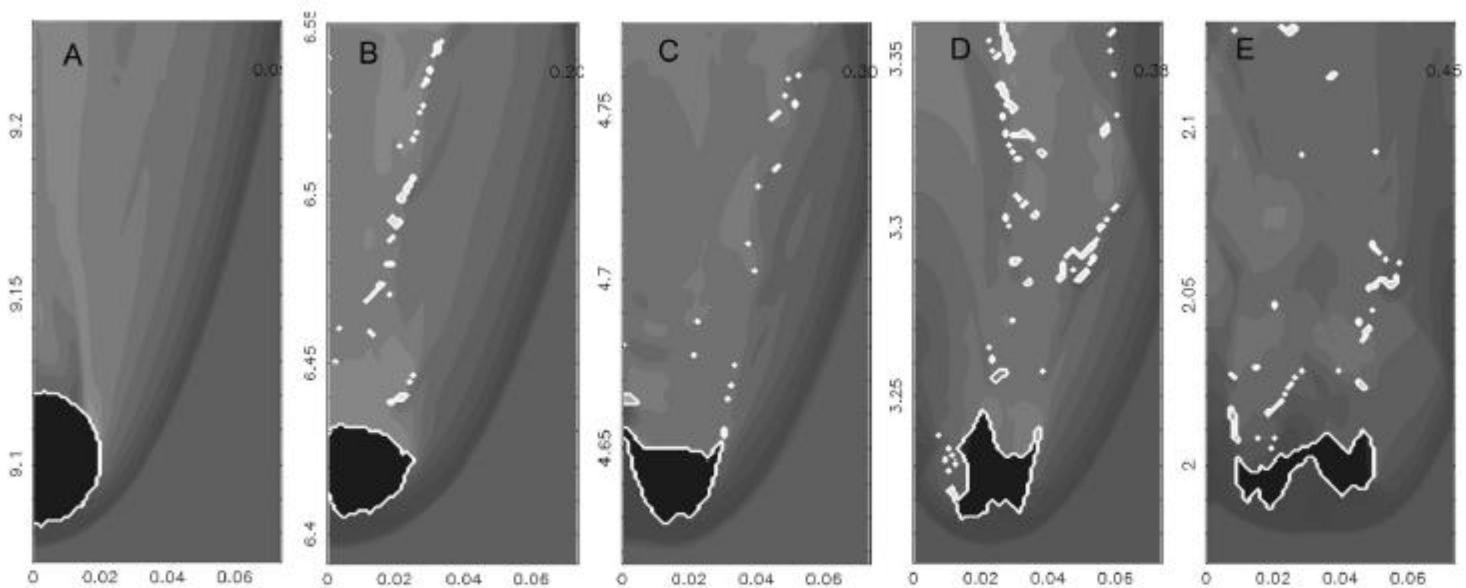
- *a point mass without disruption* (McKinley 1961), or with a simplified treatment of disruption, either
  - *the Separate Fragments (SF) model* (Passey and Melosh 1980; Artemieva and Shuvalov 1996, 2001), or

  - *the pancake model* (Chyba et al. 1993).

Asteroid Entry

- The alternative to the simplified approach is to use 4) *full-scale hydrodynamic models* in which the projectile is treated as a strengthless continuous body (Ahrens et al. 1994; Takata et al. 1994;Crawford et al. 1995), as a body with some kind of strength (Ivanov and Melosh 1994), or as a cloud of fragments (Svetsov et al. 1995).

Artemieva & Pierazzo 2009



Asteroid Entry

- Since the internal properties of comets and asteroids are poorly known, simplified approaches are competitive with more comprehensive hydrodynamic models because they allow to investigate systematically a wide range of input parameters over a short period of time.
- However, depending on the approximation used, the final results (fragments' masses, their velocities) may differ by an <u>order of magnitude.</u>

- Under the same initial conditions the no-disruption regime will provide maximum pre-impact velocity (minimum pre-atmospheric mass for reverse studies), while the pancake model with infinite projectile spreading will provide minimum pre-impact velocity (maximum pre-atmospheric mass for reverse studies).

Asteroid Entry

- **Models: solid, non deformable body**
- The projectile motion in the atmosphere is described by a set of differential equations ablation for the point mass, taking into account drag, gravity, and (for example, Melosh 1989; Chyba et al. 1993):

$$\frac{dV}{dt} = -C_D \frac{\rho_a A V^2}{2m} + g\sin(\theta)$$

$$\frac{dm}{dt} = -A \frac{C_H \rho_a V^3}{2Q}$$

- where *V* is the velocity [m/s], *t* = time [s], C_D and C_H = drag and heat transfer coefficients, ρ_a = atmospheric density [kg m^{-3}], *A* = cross-sectional area of the body [m^2], *m* = its mass [kg], *g* = gravity acceleration [m s^{-2}], *Q* = heat of ablation [J kg^{-1}], [K], and θ = path angle [deg].

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Asteroid Entry

- **Models: solid, non deformable body**
- Combined with simple kinematical equations for
- flight path angle
$$\frac{d\theta}{dt} = \frac{g\cos(\theta)}{V}$$
- altitude
$$\frac{dZ}{dt} = -V\sin(\theta)$$
- ground distance
$$\frac{dX}{dt} = V\cos(\theta)$$
- previous equations result in reasonably accurate predictions for the trajectory of a meteoroid that travels through the atmosphere without breaking up.

Asteroid Entry

- **Models: solid, non deformable body**

$$\frac{d\theta}{dt} = \frac{g\cos(\theta)}{V} - \frac{V\cos(\theta)}{R_E + Z}$$

$$\frac{dX}{dt} = \frac{V\cos(\theta)}{1 + Z / R_E}$$

- where R_E is the Earth's radius

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Asteroid Entry

- **Models: solid, non deformable body**

$$\frac{dm}{dt} = -A\frac{C_H \rho_a V^3}{Q}$$

- From observations: $C_H \approx 0.1$ for altitude > 30km

$$\frac{dm}{dt} = -A\frac{\min\left(C_H \rho_a V^3 / 2 \quad , \quad \sigma_{SB} T^4 \right)}{Q}$$

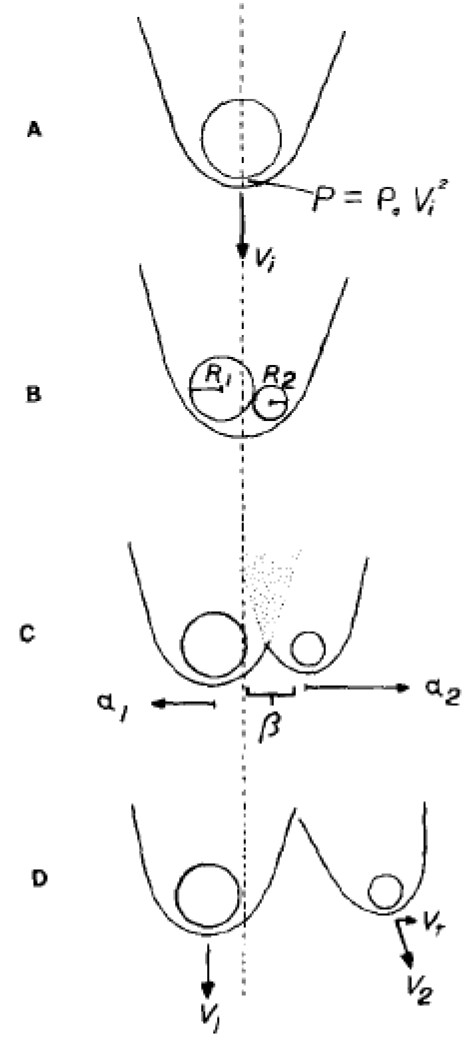
Asteroid Entry

Separate Fragments (SF) model

- Hypothesis of the disruption of an impactor traveling through the atmosphere can be traced back to Barringer's early studies of Meteor Crater on early '900
- Actual importance of atmospheric disruption for small bodies (up to a <u>few hundred meters in diameter</u>) was realized only much later.
- First analytical study, based on observations of terrestrial crater strewn fields, was carried out by Passey and Melosh (1980).
- Evolution of a disrupted body as a two-stage process:
  - 1) a strong but short interaction of the fragments immediately after the disruption, followed by
  - 2) the motion of individual fragments.

Asteroid Entry

- **Models: Separate Fragments**
- Repulsion of fragments in separated fragment (SF) models, caused by the interaction of bow shocks (Passey and Melosh 1980; Artemieva and Shuvalov 1996).



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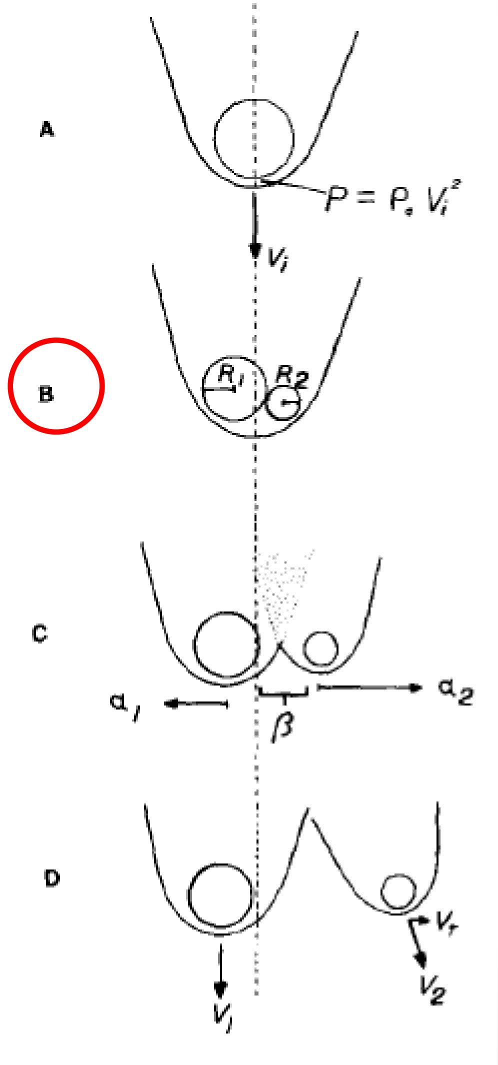
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:
- Immediately after fragmentation, the meteoroid fragments travel as a unit within a single bow shock.



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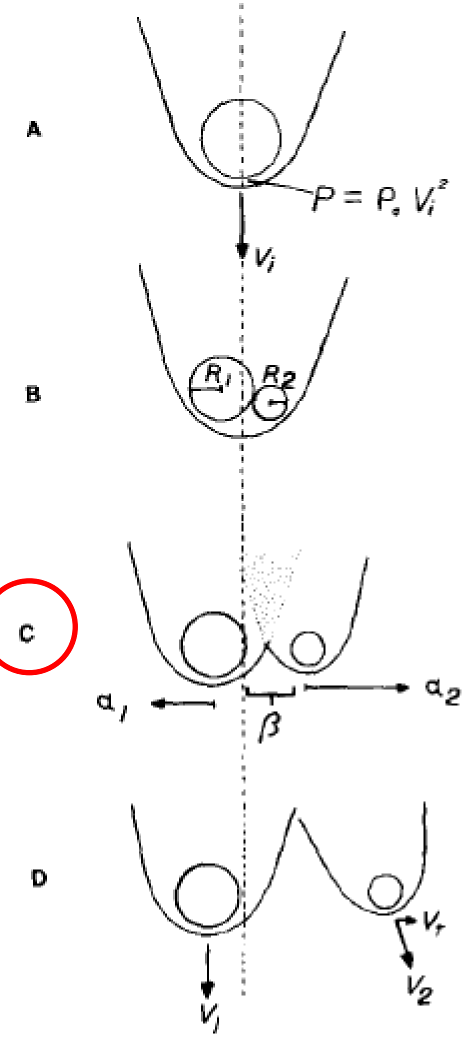
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:
- Immediately after fragmentation, the meteoroid fragments travel as a unit within a single bow shock.
- Soon afterwards the fragments become sufficiently separated that they have individual bow shocks. High pressures develop between these bow shocks, producing an acceleration transverse to the trajectory of the incoming meteoroid



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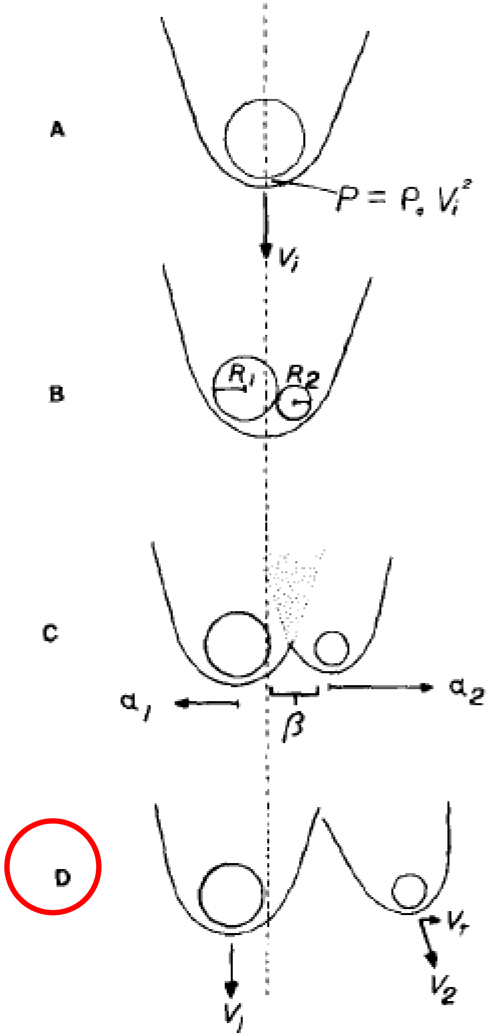
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:
- finally, the interaction of the bow shocks and the transverse acceleration cease, leaving the fragments to travel in their modified trajectories (V_1 and V_2).



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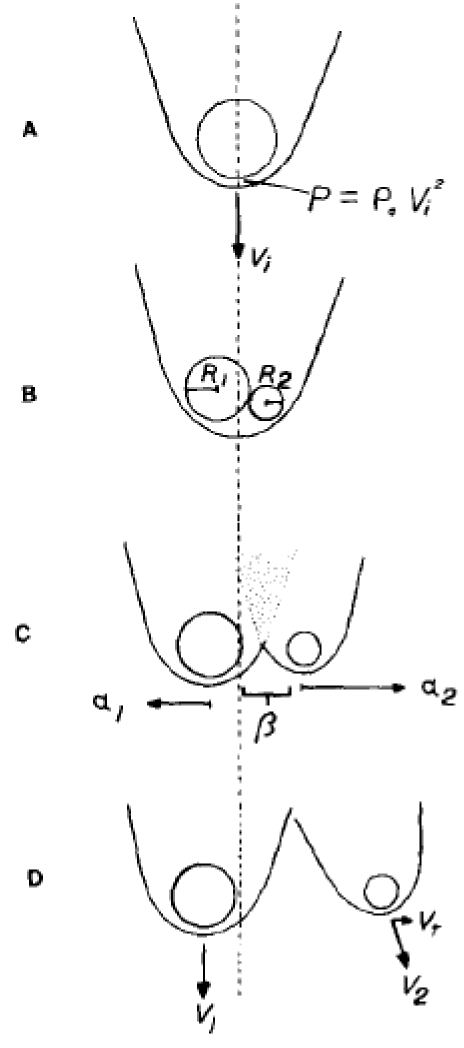
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:
- assuming that the bow shocks exert a force on each other until the two meteoroid fragments have a separation β of a certain number C of meteoroid radius R_1,

  $\beta = C R_1$
- time of interaction (a=acceleration)

$$\Delta t = \sqrt{\left(\frac{2\beta}{a}\right)}$$



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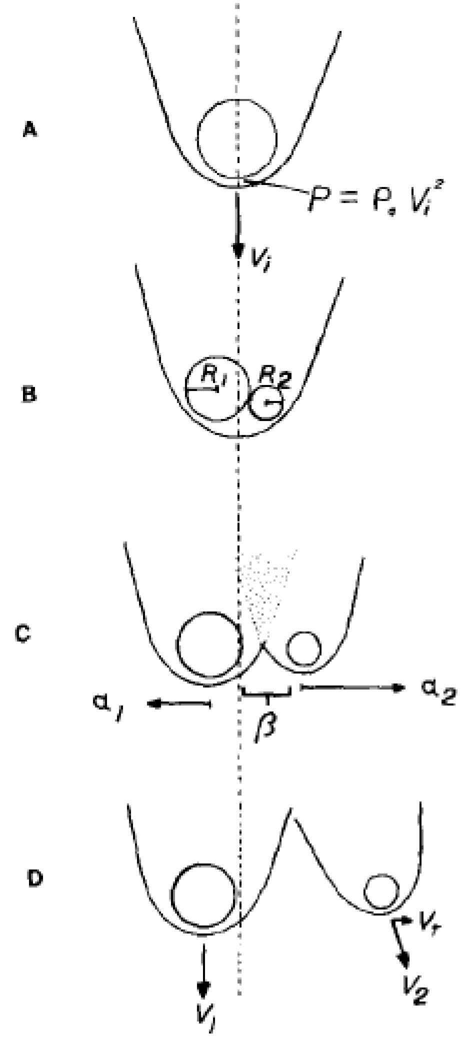
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:
- The final transverse velocity V_T is

$$V_T = a\Delta t = \sqrt{2\beta a}$$

$$a = F/m = \frac{\rho_a V_i^2 \pi R_2^2}{4/3\, \pi R_2^3 \rho_m} = \frac{3\rho_a V_i^2}{4\rho_m R_2}$$

$$V_T = \sqrt{2\beta a} = Vi\sqrt{\frac{3}{2} C \frac{R_1}{R_2} \frac{\rho_a}{\rho_m}}$$



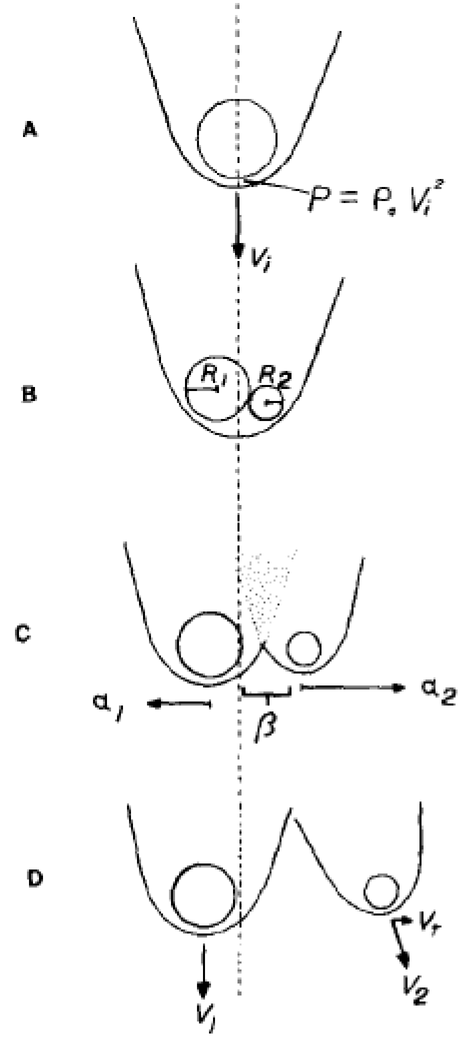
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:
- The remaining flight time

$$t_r = Z \big/ V_2 \sin\theta$$

- If assume $V_2 \approx V_i$

$$Y = V_T t_r = \sqrt{\frac{3R_1 C\rho_a}{2R_2\rho_m}}\,\frac{Z}{\sin\theta}$$



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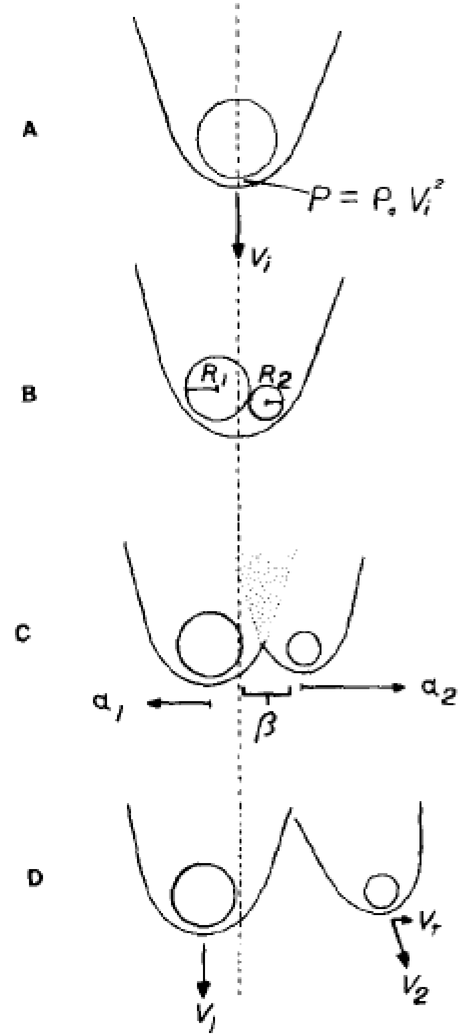
Asteroid Entry

- **Models: Separate Fragments**
- Original formulation of Passey and Melosh 1980:

$$Y = V_T t_r = \sqrt{\frac{3R_1 C\rho_a}{2R_2\rho_m}}\frac{Z}{\sin\theta}$$

- By studying the cross-range spread of craters in known crater fields, it is possible to determine an approximate value of the constant C
- Using the information on cross-range spreads, the constant C is calculated to be between 0.02 and 1.52



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Asteroid Entry

Separate Fragments (SF) model

- Passey and Melosh's analytical model was translated into a numerical model by Artemieva and Shuvalov (1996, 2001), and was named the Separate Fragments (SF) model.
- The SF model has been applied to a wide range of impactor (pre-atmospheric) masses by Bland and Artemieva (2003, 2006).

Asteroid Entry

Separate Fragments (SF) model

- The SF model considers successive fragmentations and ablations of individual fragments (where the number of fragments, N =1 at the start, and , $N \gg 1$ at the end).
- A meteoroid is disrupted into a *pair* of fragments whenever the dynamic loading exceeds its strength, which depends on the meteoroid type and size.

Asteroid Entry

Separate Fragments (SF) model

- Fragment mass and direction of separation (the two fragments move away from each other in opposite directions) are defined at random.
- Immediately after the breakup, fragments tend to have a higher strength than the parent body, but can be disrupted again into a new pair later on, when the dynamic loading exceeds the fragments' strength.
- Each fragmentation leads to a decrease in the defect number and an increase in the sub-fragment strength.
- the strength σ_f of the sub-fragment with mass m_f is determined by the relation [Weibull, 1951], $$\sigma_f = \sigma_0 \left(\frac{m_0}{m_f}\right)^a \qquad a \approx 0.25$$
- where σ_0 and m_0 are the initial parent meteoroid strength and mass.

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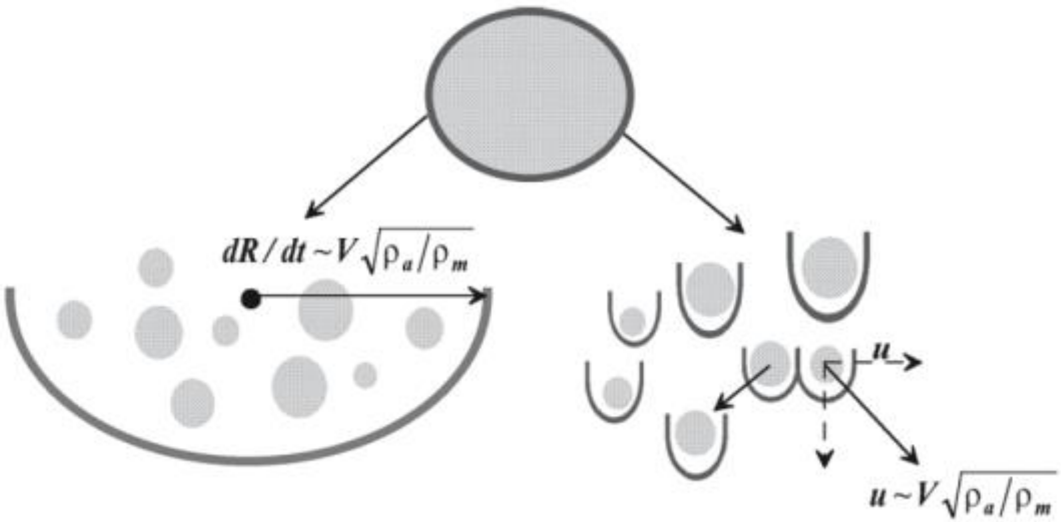
Asteroid Entry

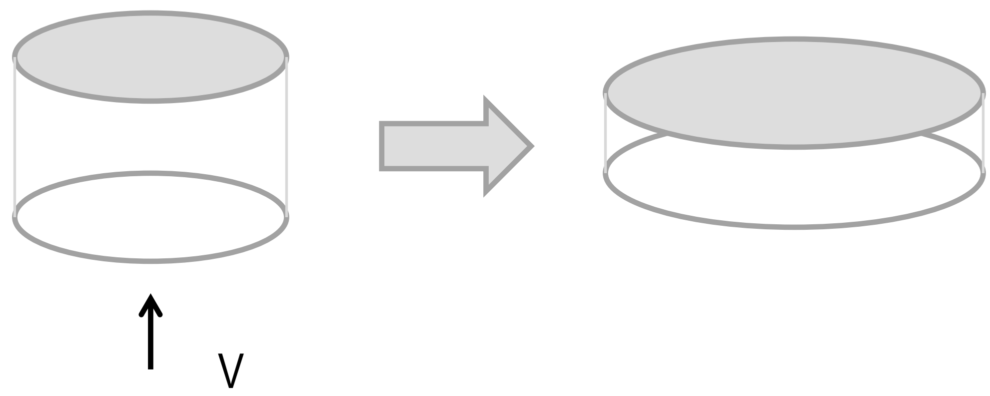
Separate Fragments (SF) model

- The model is most applicable for bodies smaller than a few meters in diameter; for larger bodies the basic assumption of “separation” among fragments becomes quickly invalid.
- In this case, a dense cloud of fragments tends to decelerate as a cloud, not as individual particles.



Asteroid Entry

- **Models: pancake**
- Equation, which describe the spreading of a disrupted body in the pancake models of Chyba et al. (1993) and Hills and Goda (1993):



$$r\frac{d^2r}{dt^2} = C_D \frac{\rho_a V^2}{\rho_m}$$

- where *r* is the projectile radius [m] and ρ_m is its density [kg m^{-3}]

Asteroid Entry

Pancake model

- Zahnle 1992; Chyba et al. 1993; Hills and Goda 1993; Collins et al. 2005.
- This simple analytical model treats the disrupted meteoroid as a deformable continuous fluid.
- Used to describe comet-like and stone meteoroids,
- Application to irons is questionable.
- Many uncertainties and “ad hoc” choices, such us the maximum allowed radius of pancaking.

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Asteroid Entry

Pancake model

- In the original model (Zahnle 1992), there were no restrictions on the growth of the pancake radius, leading to unrealistically thin and wide projectiles and to extremely low final velocities.

- Numerical models (Ivanov et al. 1992; Ahrens et al. 1994; Takata et al. 1994; Crawford et al. 1995) carried out around the same time that the pancake model was developed (i.e., the time of the collision of comet Shoemaker-Levy 9 with Jupiter) clearly showed that although flattening ("pancaking") is a typical behaviour of disrupted projectiles, it is mostly restricted to a flattening factor of 1.7–2.3.

Asteroid Entry

Pancake model

- Further, widening is arrested by the growth of Kelvin-Helmholtz (K-H) and Rayleigh-Taylor (R-T) instabilities and the resulting projectile fragmentation.
- However, commonly used restrictions on the maximum spread of the object (above 2) are purely artificial.
- Different choices of the object's maximum spread can lead to substantially different results even for identical initial conditions.
- The pancake model does not describe the object behaviour after maximum spreading is reached (would the object keep its shape and mass or would only some part of its mass reach the surface, while the rest fragments and disappears in the atmosphere?).

Asteroid Entry

Pancake model

- Large fragments may escape the cloud and continue flight as independent bodies.
- The pancake model has been reproduced by adding minor modifications to the SF model (Artemieva&Pierazzo 2009).
- This was possible because the pancake model utilizes the same equations of motion for an intact body used by the SF model (Melosh 1989, p. 206–207), with only an additional equation for spreading (Chyba et al. 1993).

- Neither the pancake model nor the SF model are realistic models for the evolution of some projectiles such as the one that produced the Canyon Diablo. An accurate reproduction of this event requires the application of full-scale hydrodynamic modelling.

Asteroid Entry

Hydrodynamic codes

- The best solution for an accurate investigation of impactor disruption in the atmosphere is through direct numerical modelling of the atmospheric entry.
- too expensive for systematic studies, considering that small bodies must be followed through distances exceeding by far their diameter (∼50m versus 20–50 km).
- This causes obvious computation cost versus resolution issues, especially considering that internal properties of incoming objects (shape, strength, porosity, homogeneity) are still poorly known. This approach, therefore, can only be used for investigating a few test cases, after a more systematic investigation has been carried out with the simpler models.

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Hydrodynamic codes

- To model the atmospheric deceleration of a projectile, initial stage of the crater formation (compression and excavation), and high-velocity material ejection, such as the 3D hydrocode SOVA (Shuvalov 1999) coupled to equation of state tables for the materials involved in the simulations.
- SOVA is a two-step Eulerian code that can model multidimensional, multimaterial, large deformation, strong shock wave physics.

Asteroid Entry

Hydrodynamic codes

- It includes a general treatment of viscosity for modelling viscous flow with Newtonian or Bingham rheology, while the implementation of the Rigid-Plastic Model (RPM; Dienes and Walsh 1970; Shuvalov and Dypvik 2004) allows to mimic plastic behaviour of the projectile.
- In addition, SOVA can describe the motion of solid/melt particles in an evolving ejecta-gas-vapor plume and their momentum-energy exchange using two-phase hydrodynamics, which takes into account both individual particle characteristics (mass, density, shape) and their collective behaviour (momentum and energy exchange with surrounding gas).

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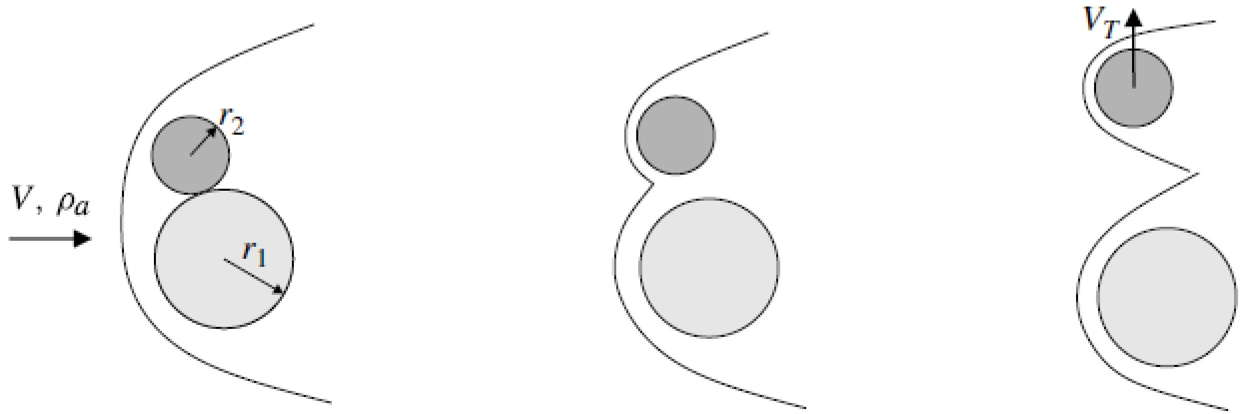
Asteroid Entry

New developments



$$V_T = V\sqrt{\frac{3}{2}C\frac{r_1}{r_2}\frac{\rho_a}{\rho_m}}$$

- does not adequately predict the separation behaviour of unequally sized bodies

(Laurence, et All 2012)

Asteroid Entry

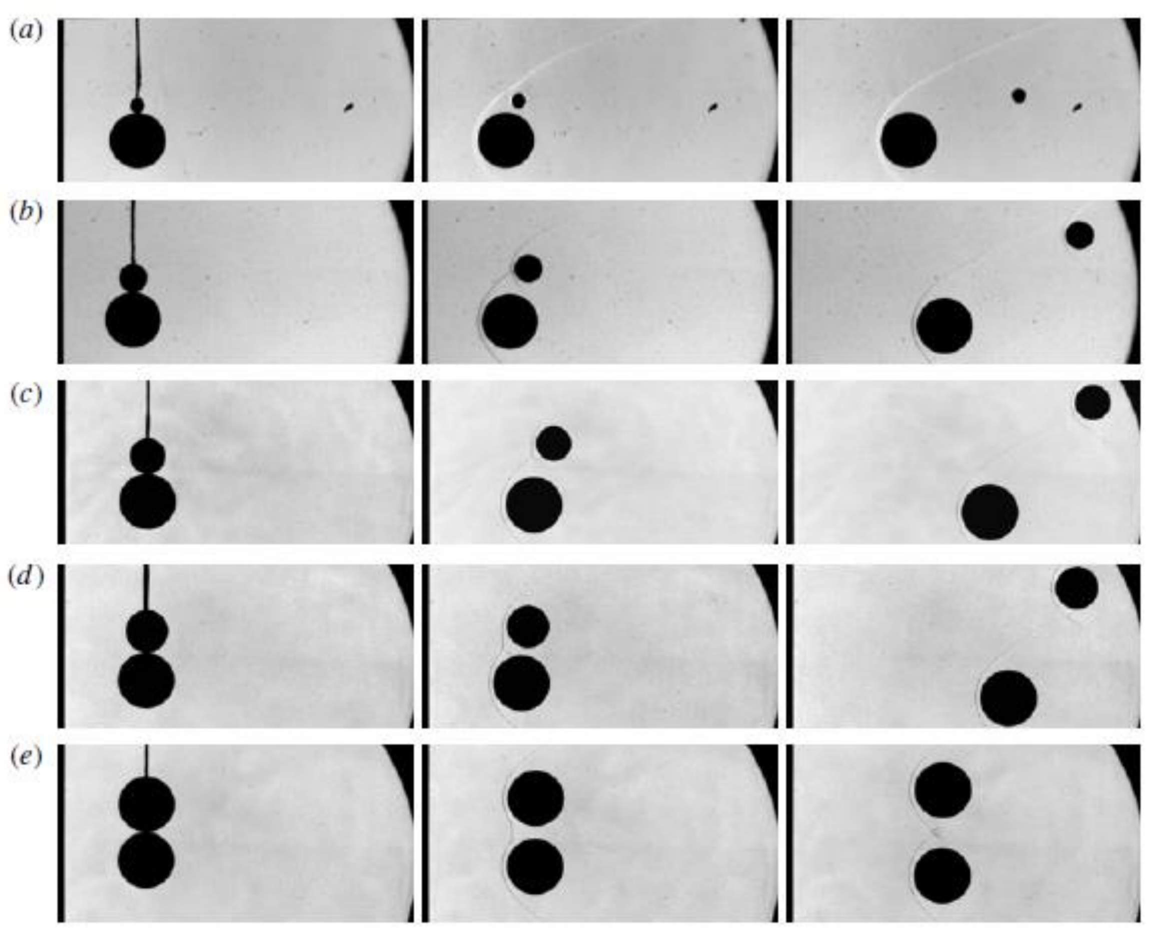
New developments

- The original assumption was: purely lateral separation
- Actually: the smaller (secondary) body is subject to a higher axial acceleration and thus travels both laterally and downstream relative to the larger (primary) body.
- “shock-wave surfing”: the secondary body traces a trajectory so as to follow the bow shock of the primary body downstream.
- significantly larger lateral velocity because the interacting flow field produces a substantial repulsive lateral force on the secondary body.

(Laurence, et All 2012)

Asteroid Entry

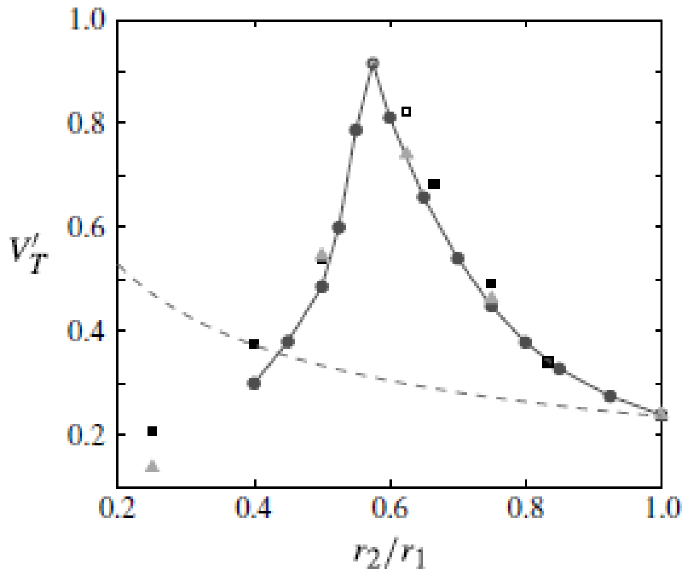
New developments

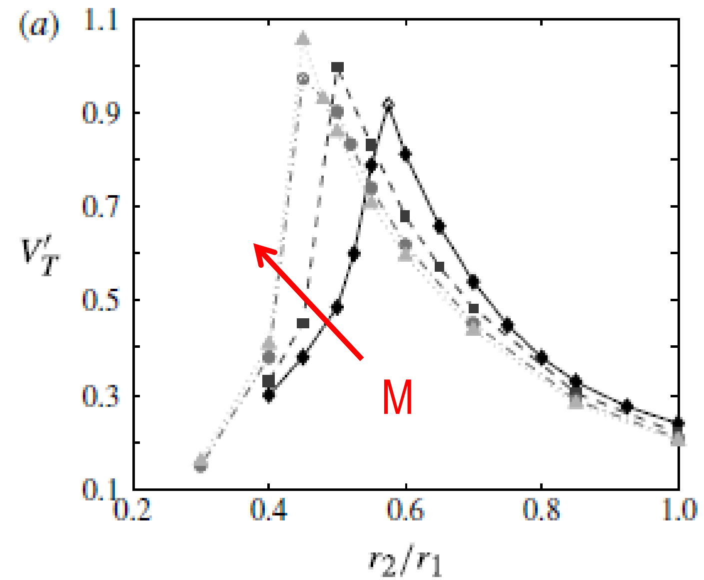


(Laurence, et All 2012)

Asteroid Entry

New developments





$$V_T = V\sqrt{\frac{3}{2}C\frac{r_1}{r_2}\frac{\rho_a}{\rho_m}}$$

(Laurence, et All 2012)

$$V_T^{'} = \frac{V_T}{V\sqrt{\frac{\rho_a}{\rho_m}}} = \sqrt{\frac{3}{2}C\frac{r_1}{r_2}}$$

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Summary

- (Re)-Entry and Hypersonic Flows
  - Introduction to flow regimes and hypersonic phenomena (shock waves and heating)
- Re-entry and evolution of Space Debris
  - Introduction (statistics, and hazard & risk assessment)
  - Main tools and used methods
- Entry and evolution of Asteroids/Comets
  - Introduction
  - Main methods and some recent advances

“Space Debris and Asteroids (Re)Entry Analysis Methods and Tools"

END

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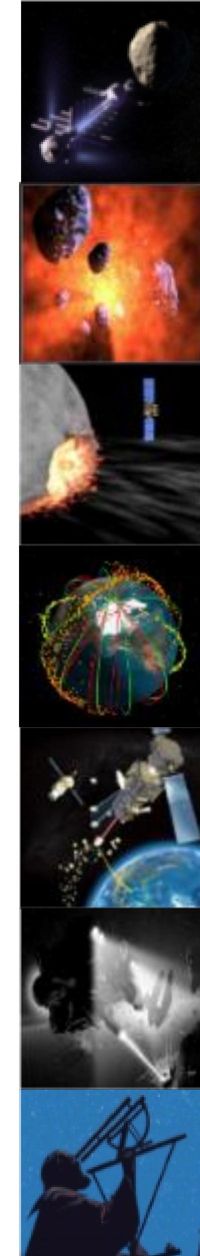
PEOPLE

MARIE CURIE ACTIONS



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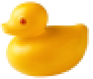

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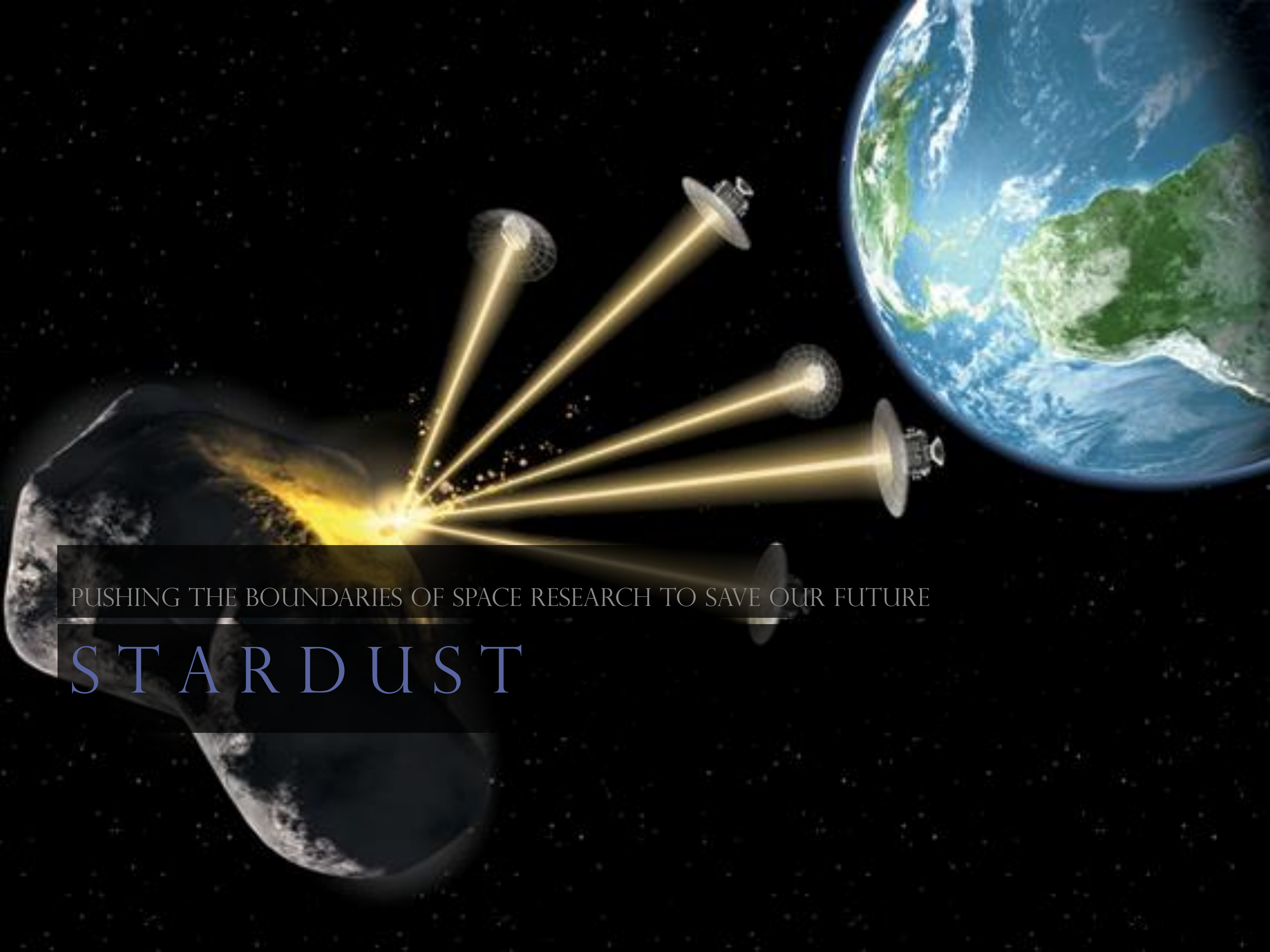
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