Improvements in Modeling Radiant Emission from the Interaction Between Spacecraft Emanations and the Residual Atmosphere in LEO

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Outline

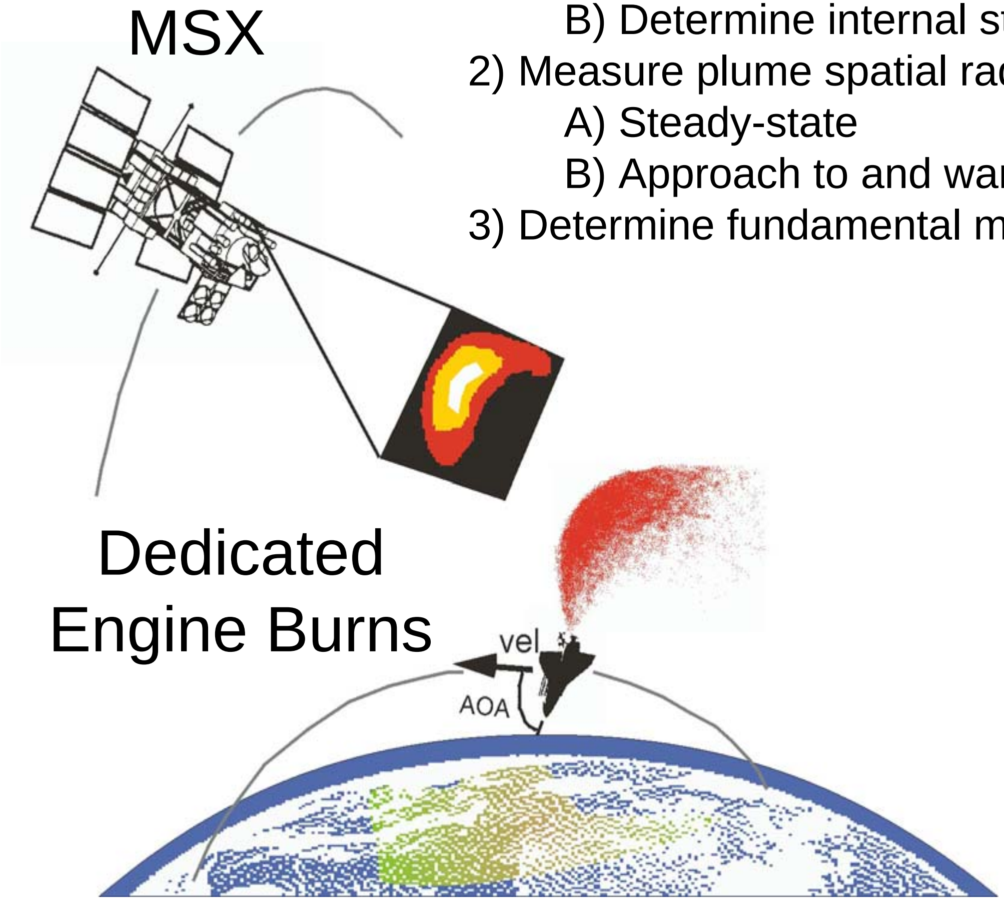
- Introduction and Background
- Potentials Valid at Hyperthermal Energies
- Improved Deflection Function
- Validation
- Implementation of Improvements
- Review of Atomic and Molecular Cross-sections
- Summary & Conclusions

Introduction and Background

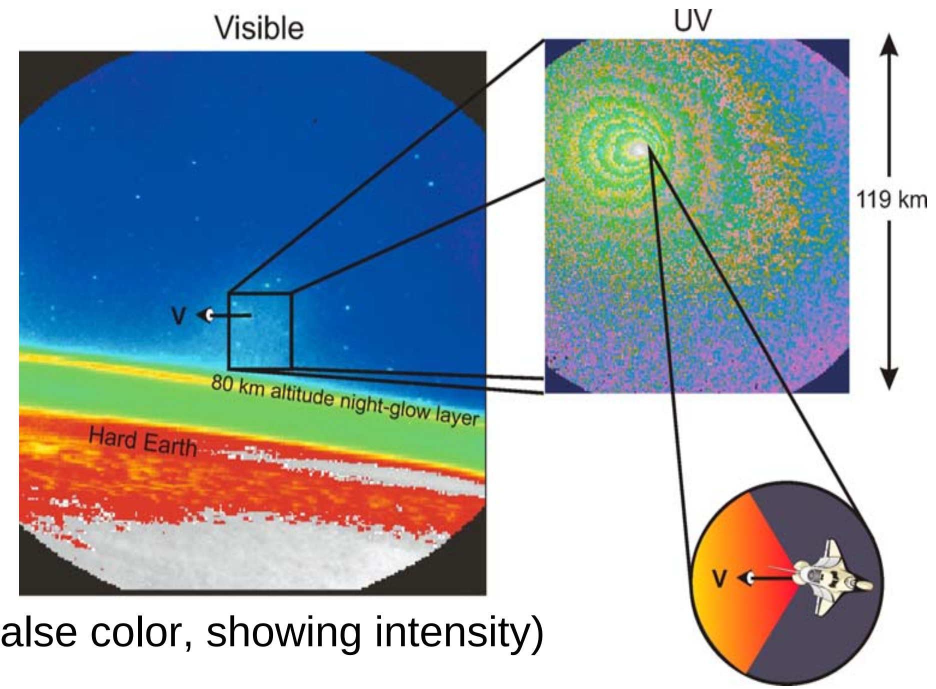
Data Which Revealed Need

Shuttle Plume Observations Experiment

1) Measure plume spectral radiance
    A) Identify emitters
    B) Determine internal state distributions
2) Measure plume spatial radiance from emitters
    A) Steady-state
    B) Approach to and wane from steady-state
3) Determine fundamental mechanisms

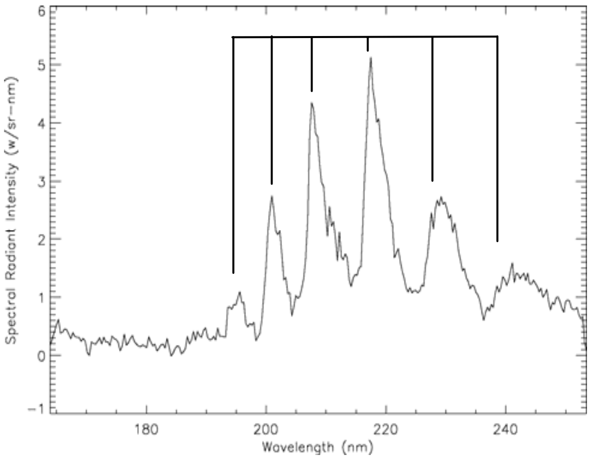


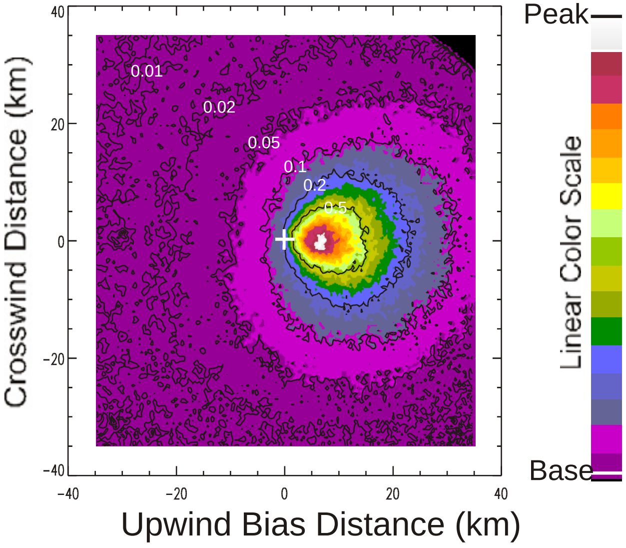
CO Cameron Band Emission



(false color, showing intensity)

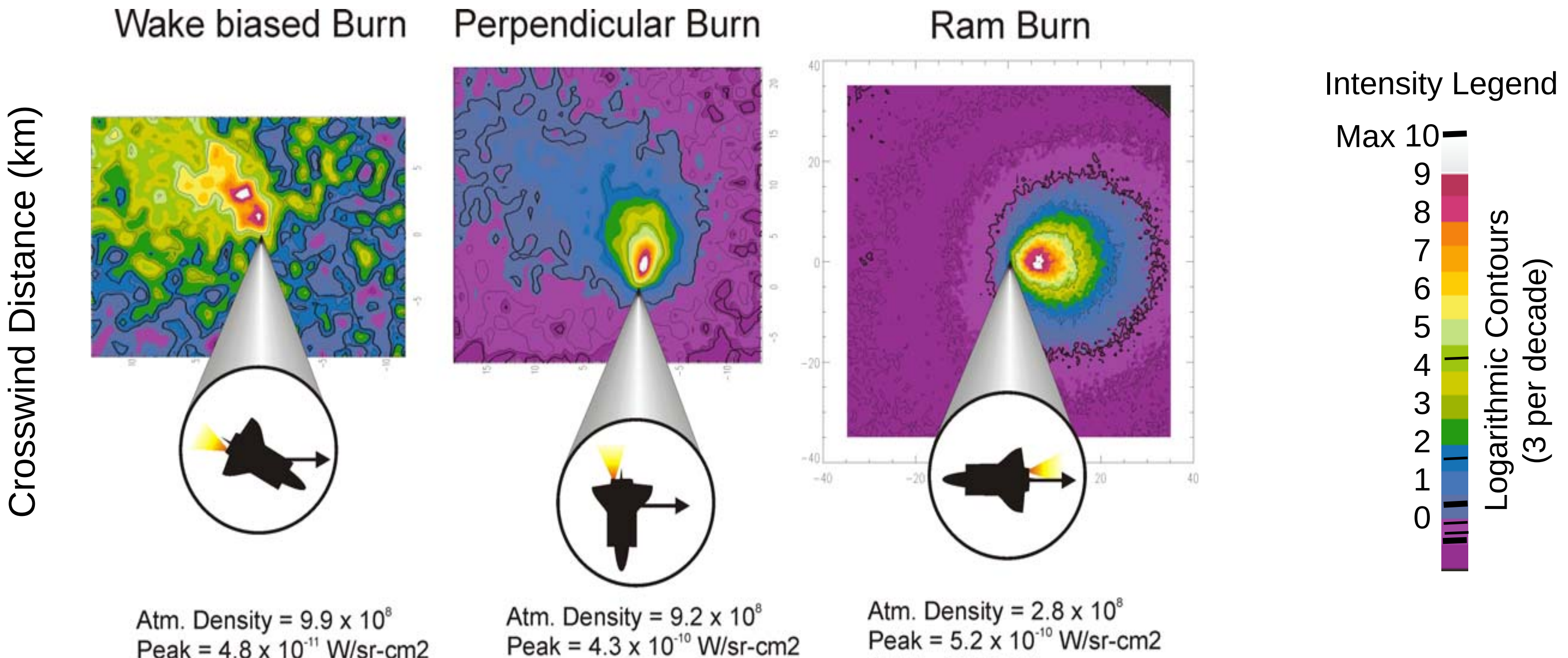
OMS Ram Burn
298 km Alt.



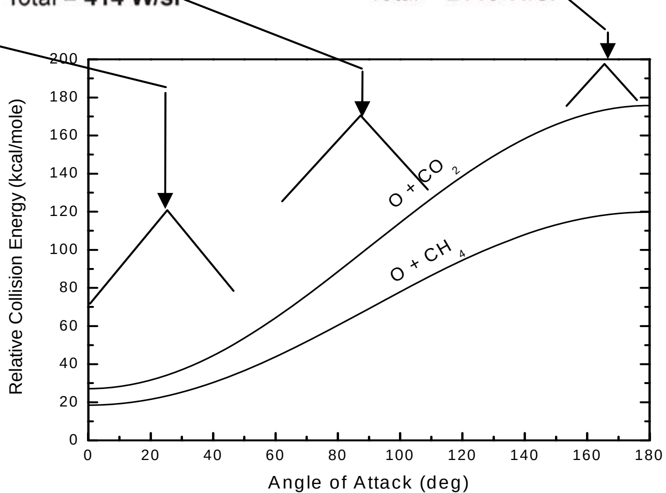


Total intensity = 1940 W/sr
~1 photon/10,000 plume molecules

AOA Dependence



Wake biased Burn	Perpendicular Burn	Ram Burn
Atm. Density = 9.9×10^8	Atm. Density = 9.2×10^8	Atm. Density = 2.8×10^8
Peak = 4.8×10^{-11} W/sr-cm2	Peak = 4.3×10^{-10} W/sr-cm2	Peak = 5.2×10^{-10} W/sr-cm2
Total = **31 W/sr**	Total = **414 W/sr**	Total = **2140 W/sr**



Atmosphere Composition

O	0.7 – 0.9
N_2	0.1 – 0.26
O_2	0.003 - .01
O^+	0.0005 - .0001

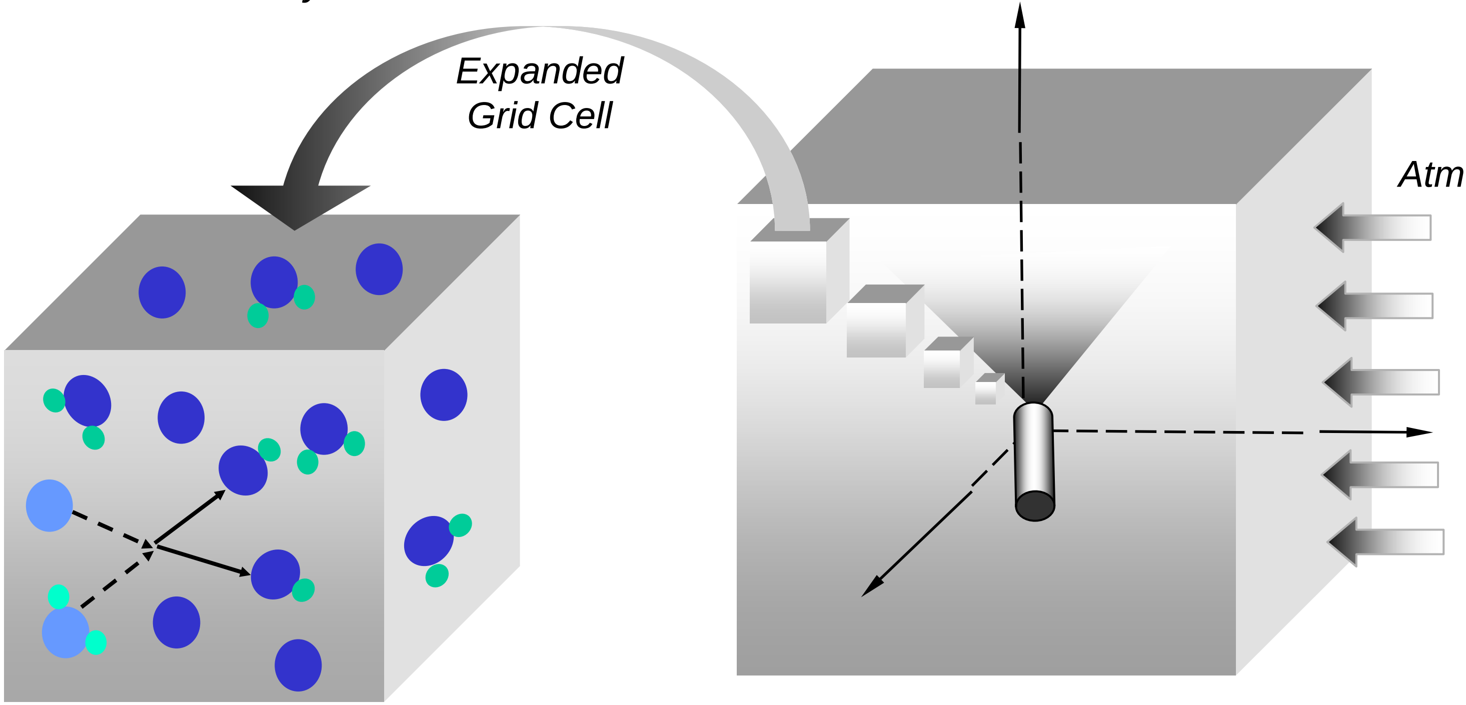
Exhaust Composition

H_2O	0.32
N_2	0.31
H2	0.17
CO	0.12
CO_2	0.05
H	0.015

Plume Modeling

*SOCRATES: Direct Simulation Monte Carlo (DSMC)**

**G.A. Bird, "Molecular Gas Dynamics and the Direct Simulation of Gas Flows", Clarendon Press, Oxford, 1994.*



DSMC algorithm

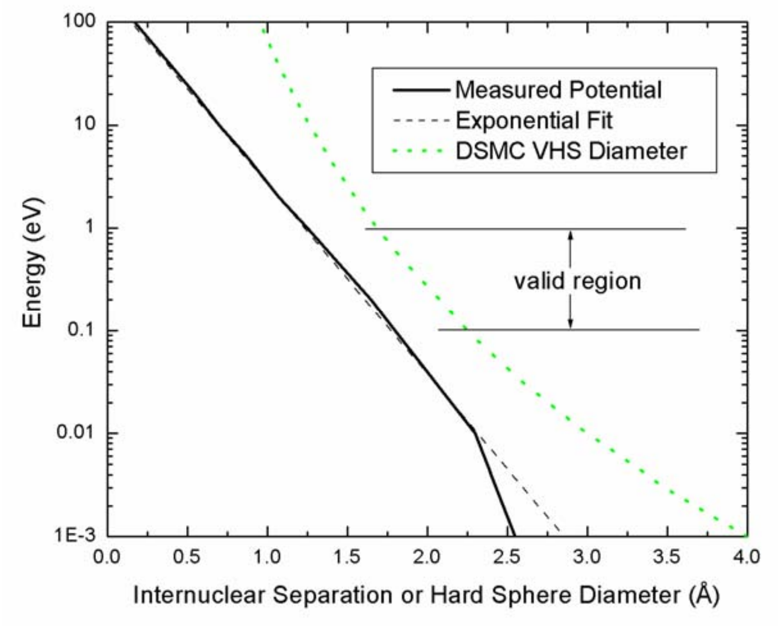
- *Advance Molecules*
- *Simulate Collisions*
- *Sample Outcomes*

Macroscopic quantities are determined from statistical averages of microscopic events

~10^6 "particles"
~10^4 grid cells

Interactions must be simple to minimize computational burden

Variable Hard Sphere (VHS) Model



Particle sizes determined from

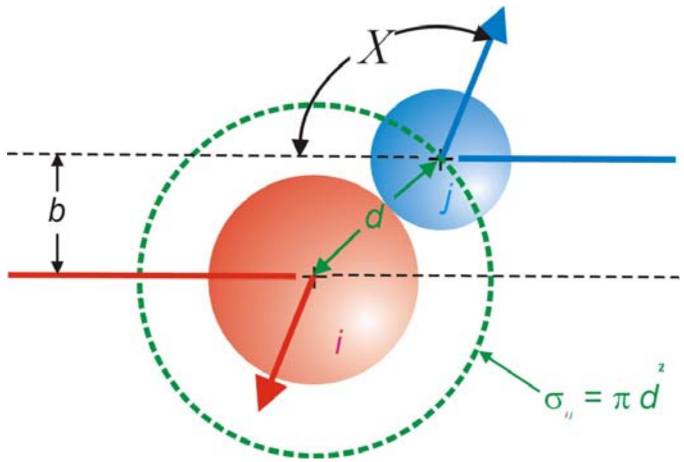
$$E = A / d^{n} \quad (n = 8) \qquad (1)$$

Which conveniently yields

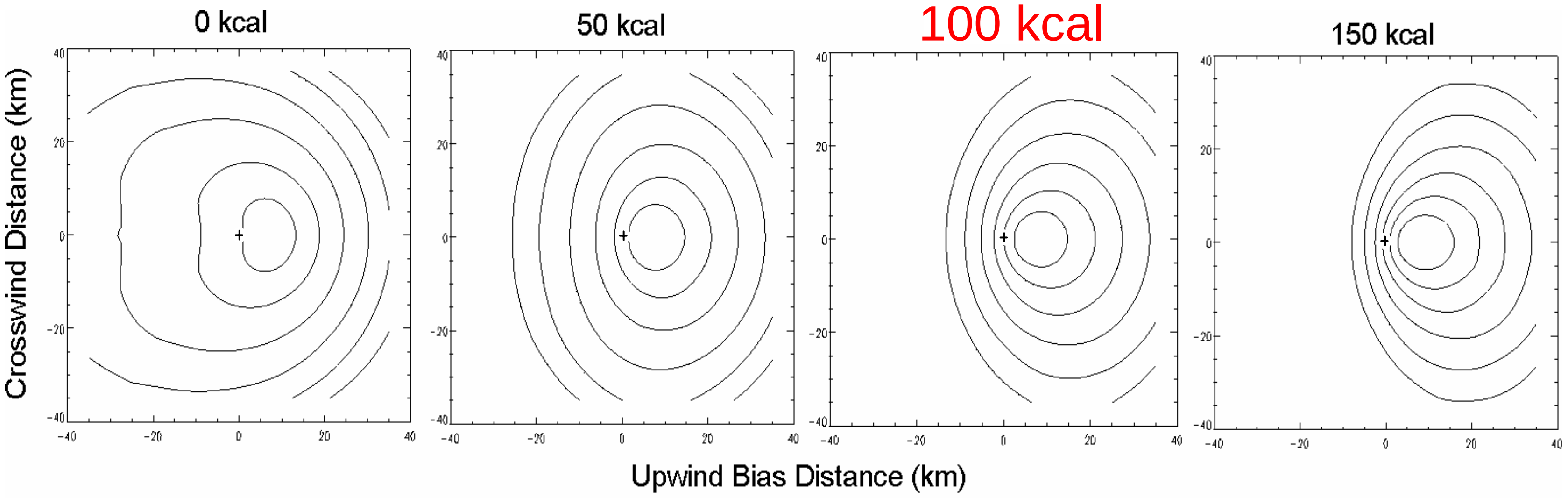
$$\sigma(E) = A_{ii} E^{-2/n}$$

(unique A_{ii} from A for each species)

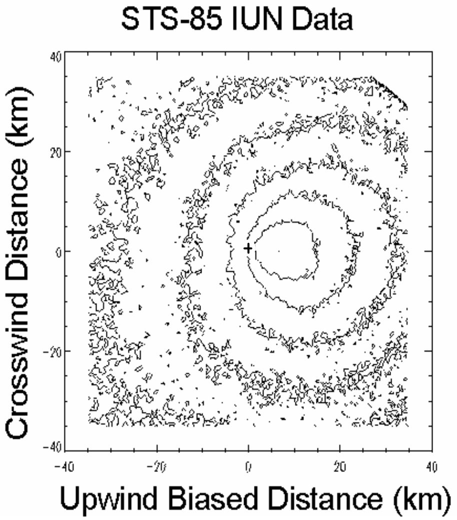
But Eq. (1) diverges from potential at hyperthermal energies.

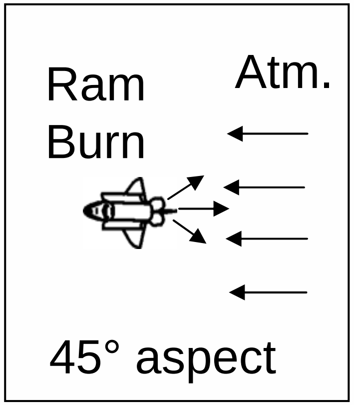


Sensitivity to Activation Energy



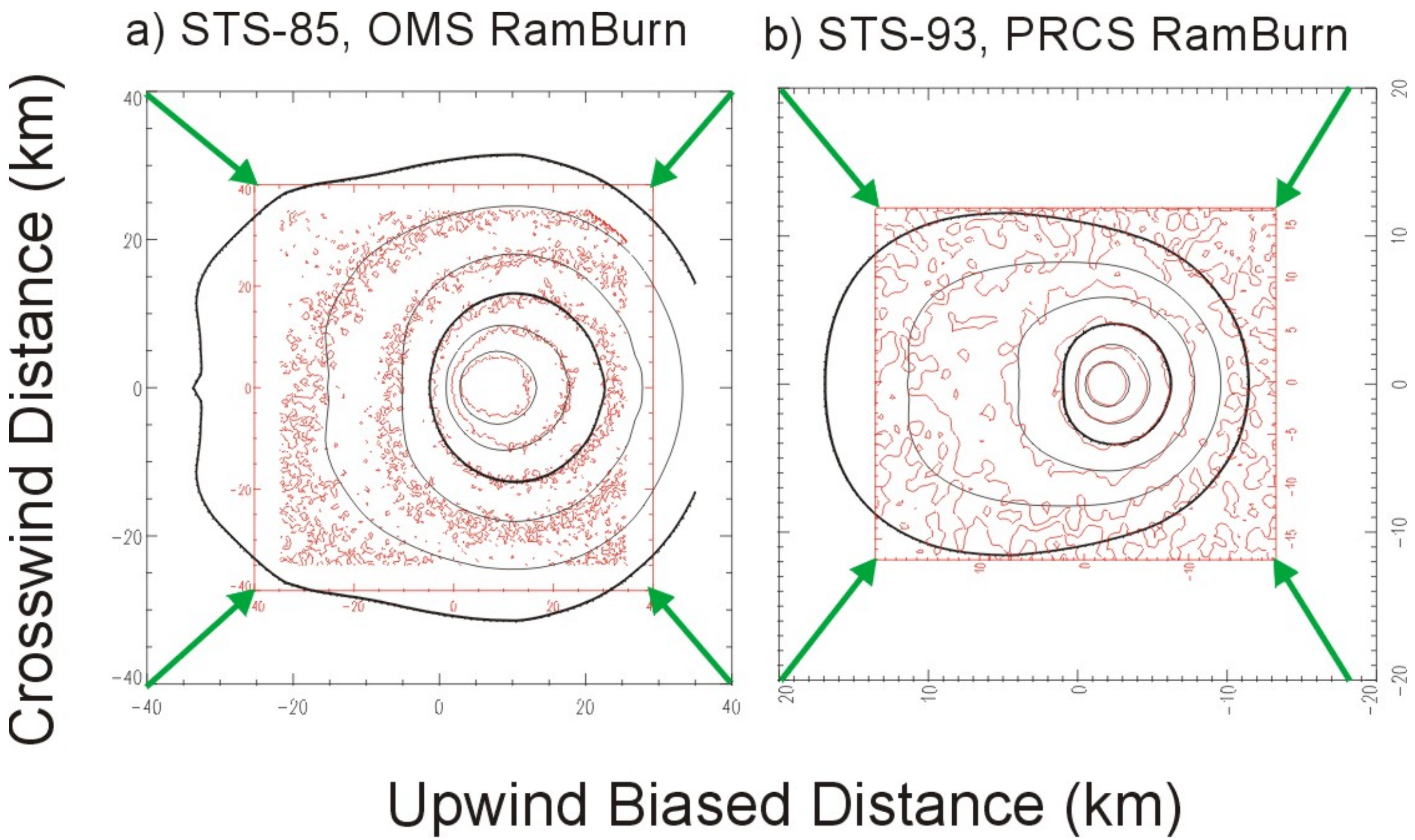
Monte Carlo analysis of UV plume as 2-step mechanism sensitive to ACTIVATION ENERGY in the final step.





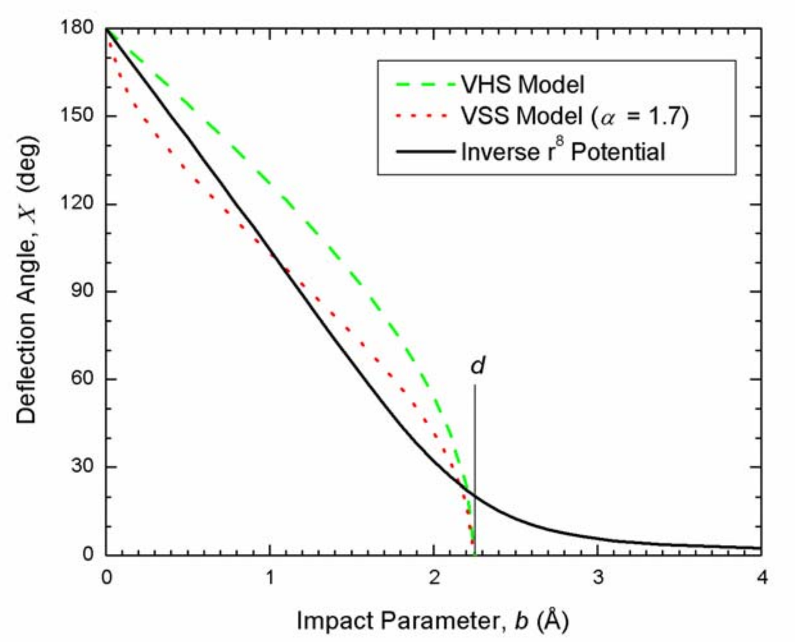
Plume Size Mismatch

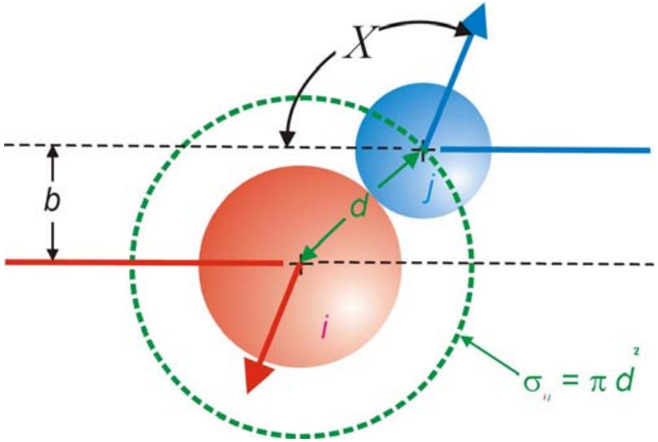
Analysis indicates mismatch between observed and modeled plume sizes for collisions at hyperthermal energies.



Data compressed to match model

Scattering Deflection Functions





VHS scattering is isotropic:

$X_{VHS} = 2\cos^{-1}(b/d)$

Variable Soft Sphere (VSS) model modifies distribution to be closer to integrated trajectory scattering from potential

$X_{VSS} = 2\cos^{-1}[(b/d)^{1/\alpha}]$

Potentials Valid at Hyperthermal Energies

Inert Gas Diameters

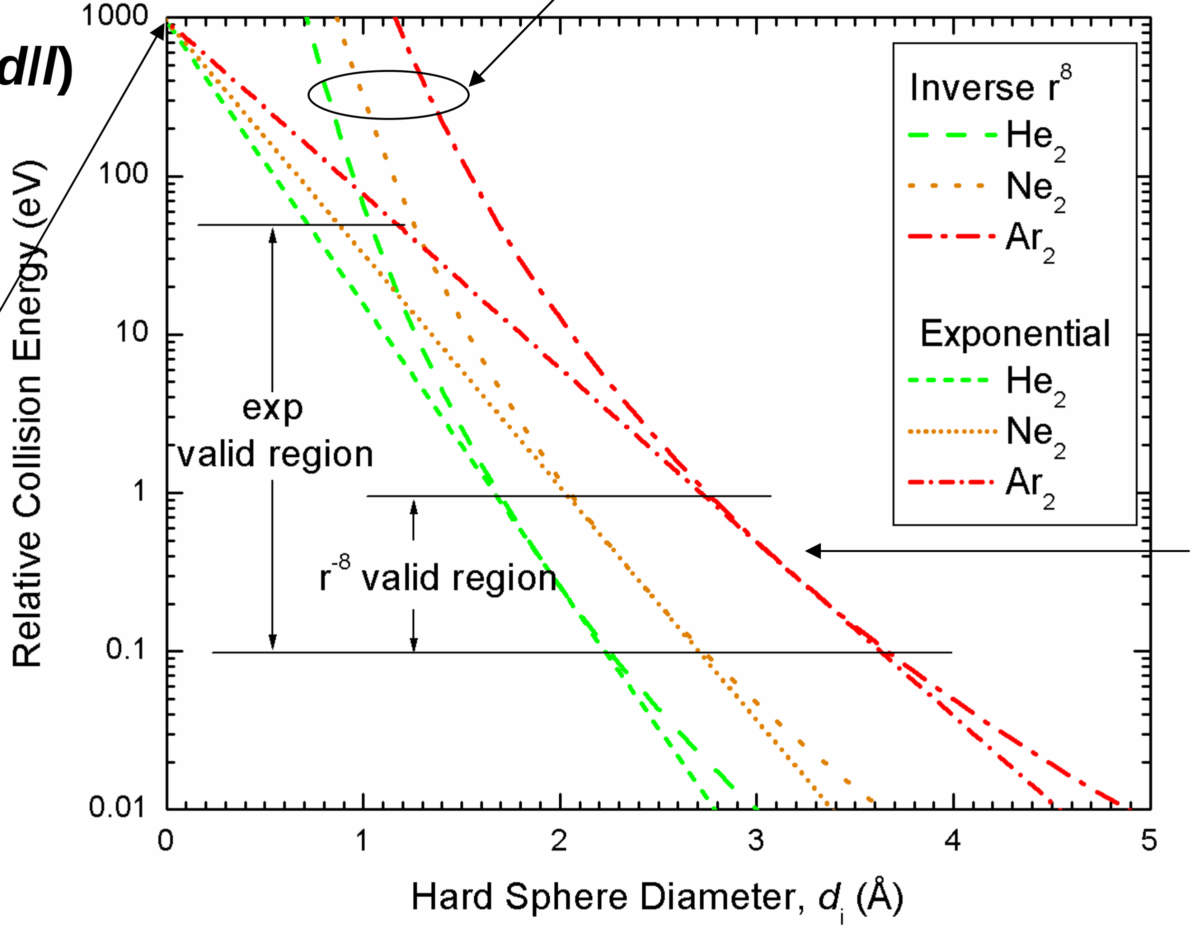
Exp fit

$E = A'\exp(d/l)$

found to have common intercept

VHS Model

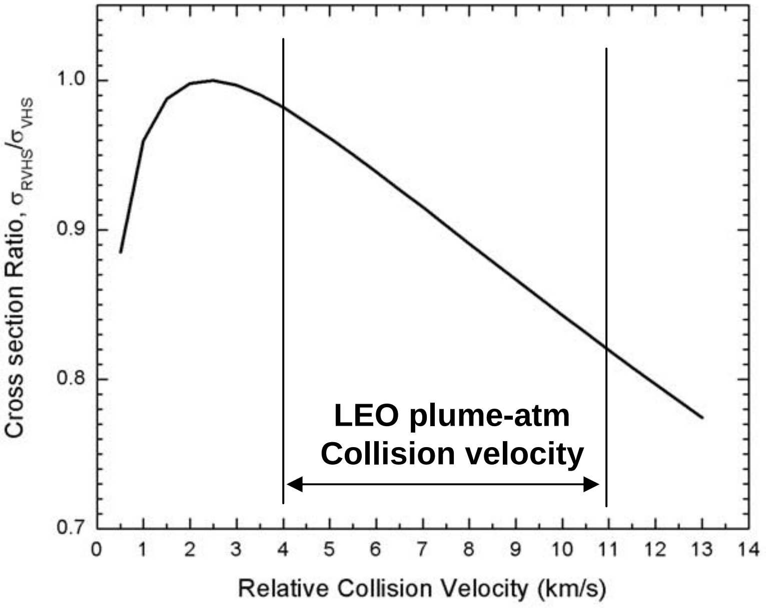
$E = A/d^{8}$



Exp fit to match slope at reference value

Refined VHS Model (RVHS)

$\sigma_{\mathrm{RVHS}}/\sigma_{\mathrm{VHS}}$ **ratio**



VHS Model

One parameter, A_{ii} (n constant = 8)

$$\sigma_{ij\ \mathrm{VHS}}(E) = A_{ij}\, E^{-2/n}$$

$$A_{ij} = [(A_{ii}^{1/2} + A_{jj}^{1/2})/2]^2$$

RVHS Model

One parameter, l_{ii} (A'_{ij} const. = 1000)

$$l_{ii} = (A_{ii}/\pi)^{1/2}/(n\, E_{\mathrm{ref}}^{\ 1/n})$$

$$l_{ij} = (l_{ii} + l_{jj})/2$$

$$\sigma_{ij\ \mathrm{RVHS}}(E) = \pi\, l_{ij}^2\, (\ln A'_{ij} - \ln E)^2$$

Or two parameter (more flexible):

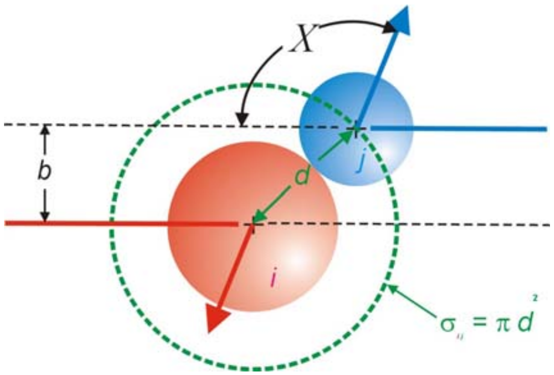
$$A'_{ij} = \exp[(l_{ii} \ln A'_{ii} + l_{jj}\, A'_{jj})/(l_{ii} + l_{jj})]$$

RVHS Model valid at hyperthermal energies to ~50 eV.

Improved

Deflection Function

Ar-Ar Scattering Deflection at 1 eV

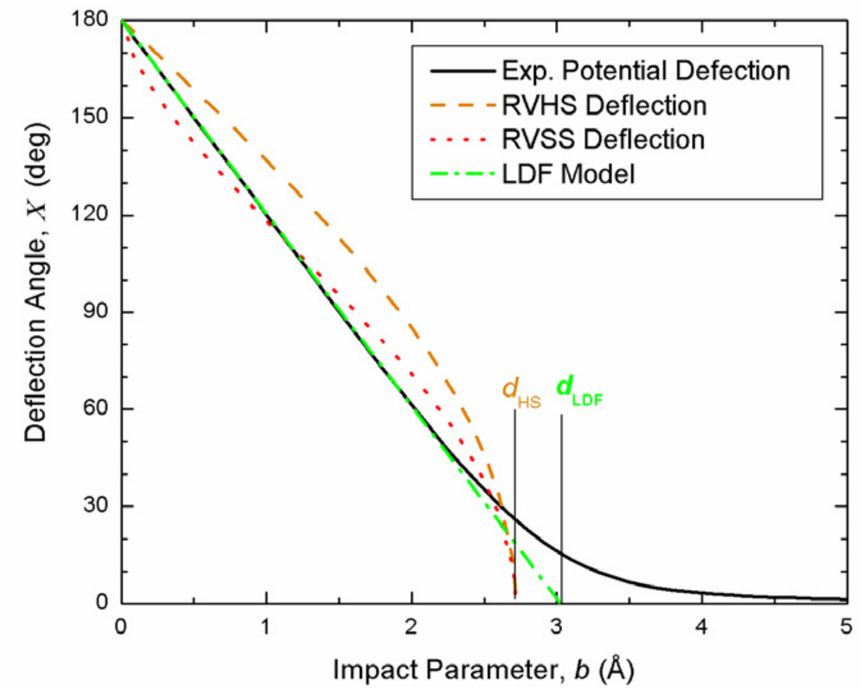


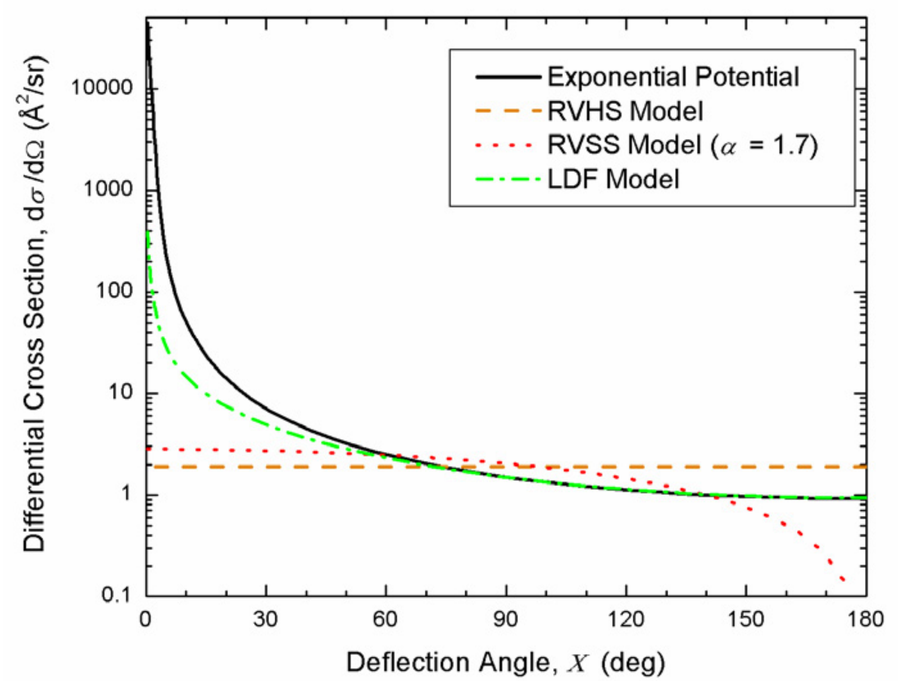
VHS isotropic scattering:

$$\chi_{VHS}(b) = 2\cos^{-1}(b/d_{HS})$$

Linear Deflection Function (LDF):

$$\chi_{LDF}(b) = \pi(1-b/d_{LDF}) = \pi(1-0.82\,b/d_{HS})$$

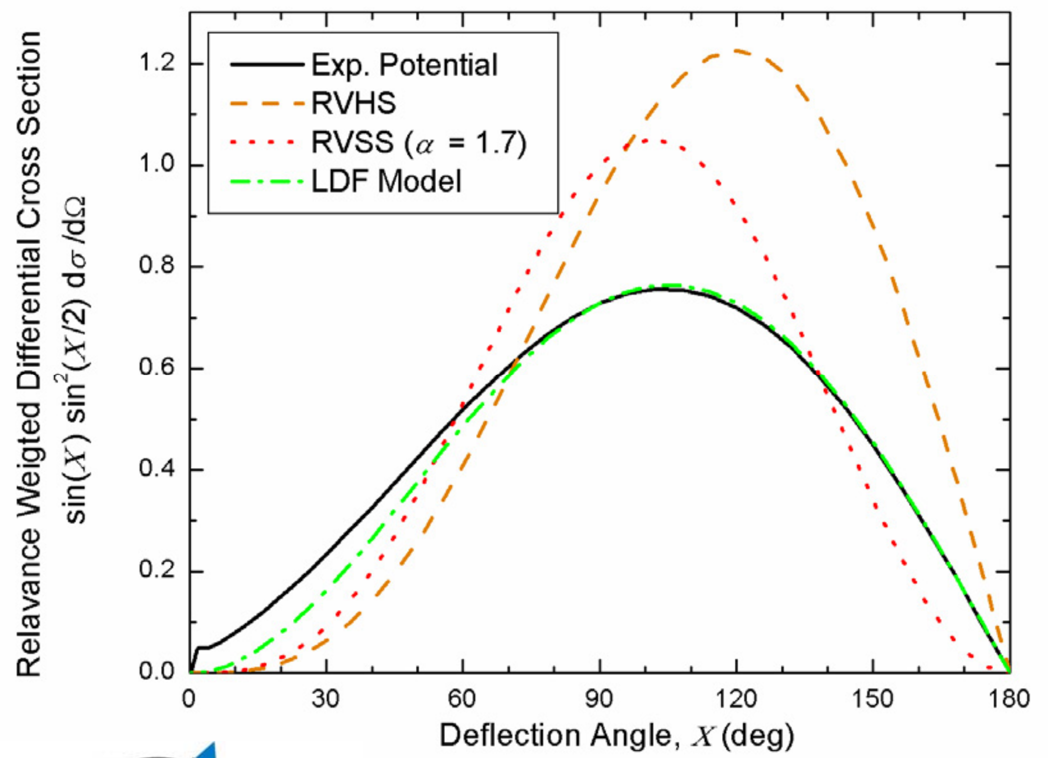


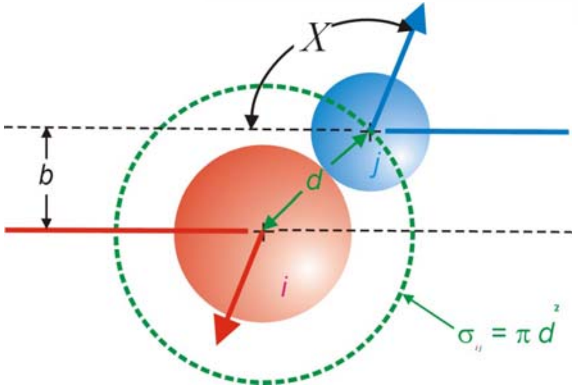


Relevance Weighted Deflection

Weighting factors

1) Sin(X) azimuthal dependence of accessible solid angle.
2) Sin($X/2$) location changing dependence.
3) Sin($X/2$) momentum transfer impacting subsequent collisions.





Mismatched Area

VHS = 54%

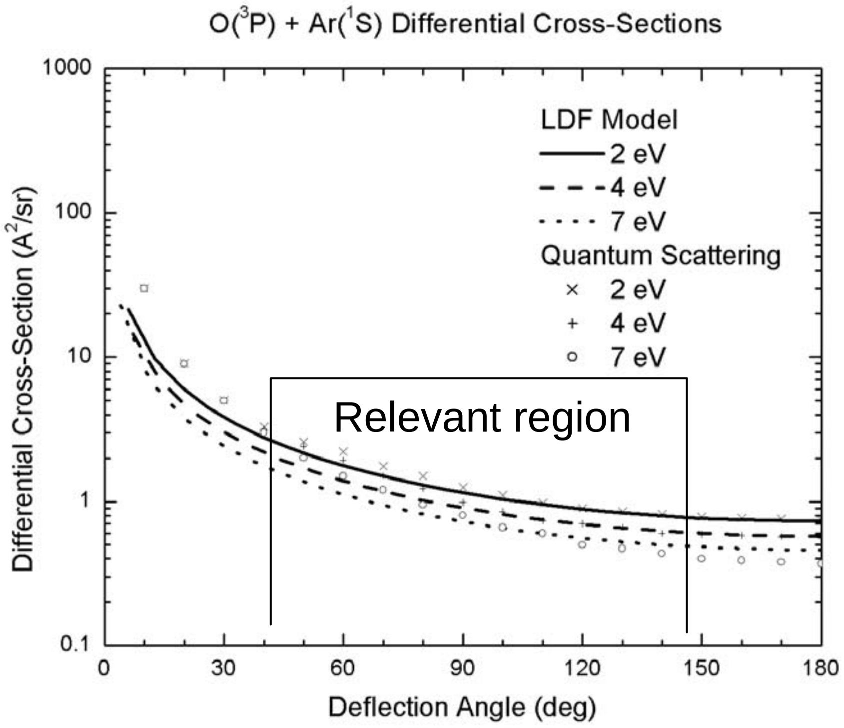
VSS = 30%

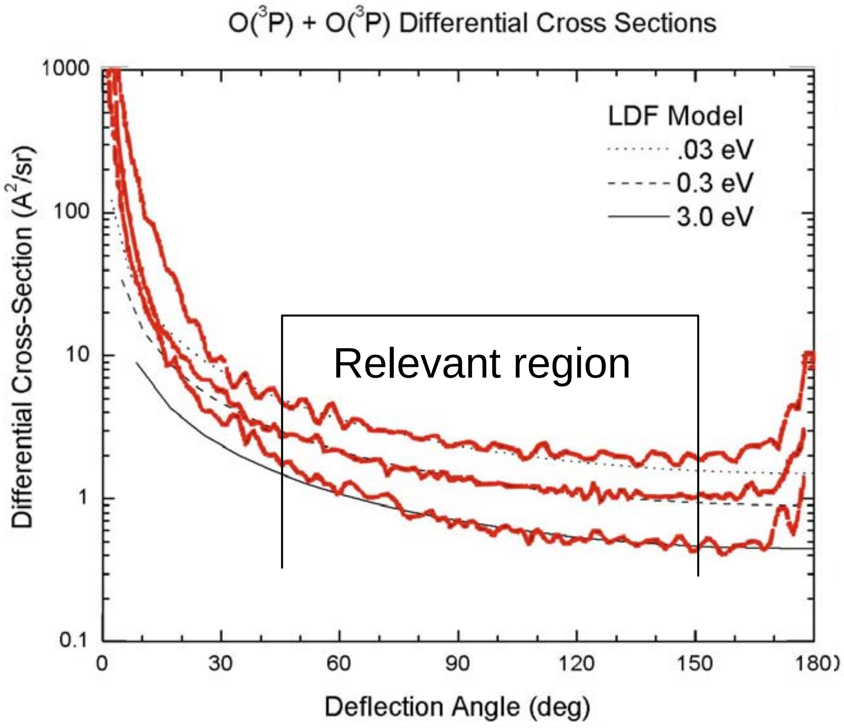
LDF = 5%

Validation

Comparison of RVHS/LDF Model to Theoretical QM Scattering

QM scattering represents statistical averages over multiple surfaces, representing approach orientations





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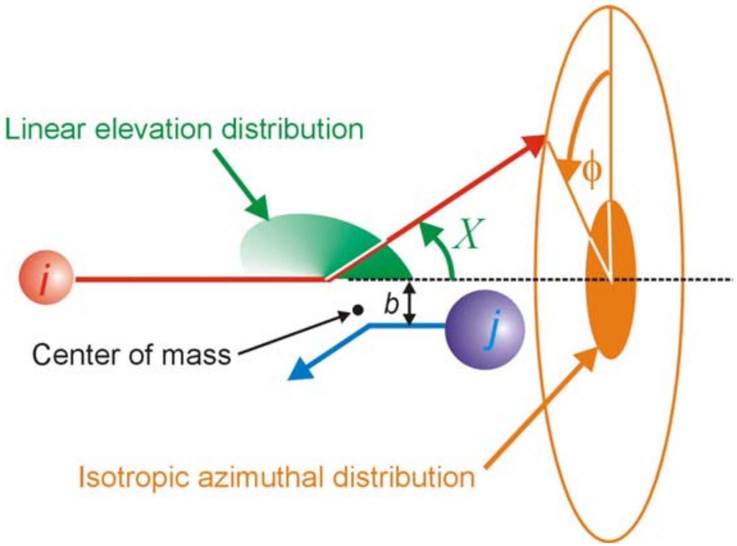
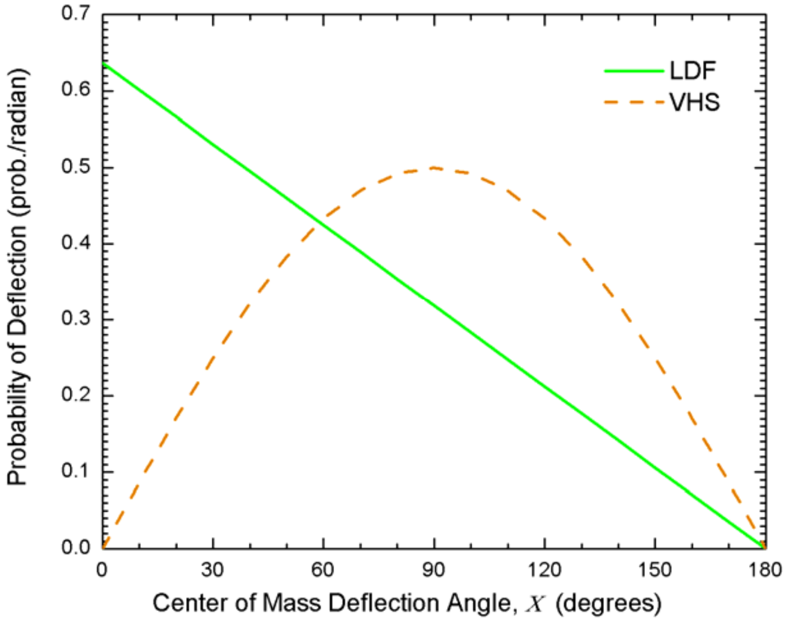
Implementation of Improvements

Deflection Probability



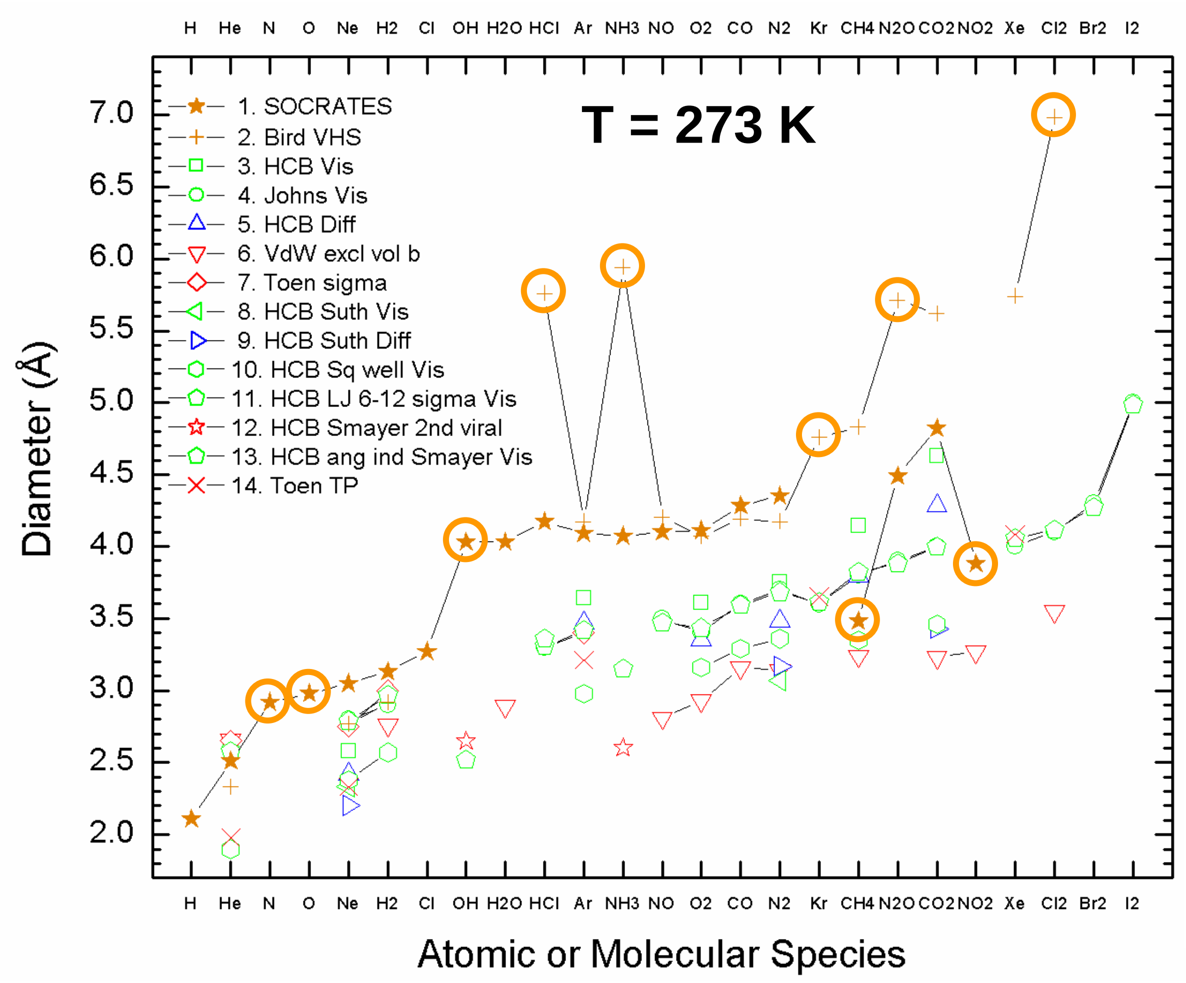


Probability of deflection described by:

$P(X) = 2(\pi - X)/\pi^2$ **(probability per radian)**

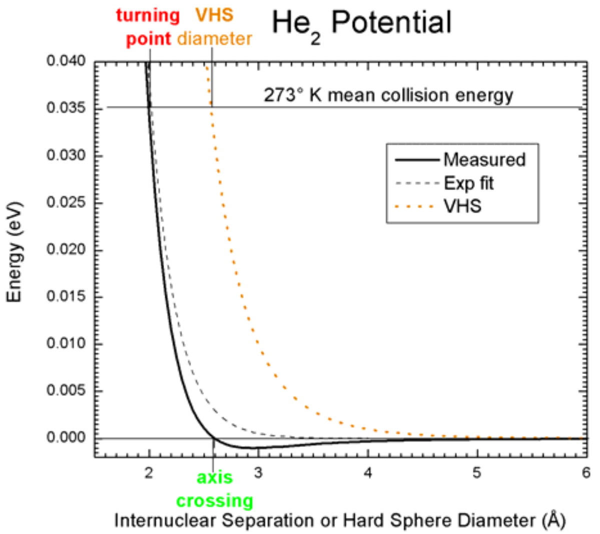
Review of Atomic and Molecular Cross Sections

Review of Atomic and Molecular Cross-Sections



○ = questionable

Cross-section definitions vary



Summary & Conclusions

Summary & Conclusions

- Current VHS & VSS models use cross sections that are too large at hyperthermal energies.
- Current VHS & VSS scattering may predict erroneous plume shapes in LEO conditions.
- Hard sphere sizes tied to an exponential potential can extend DSMC to hyperthermal collision energies up to ~50 eV.
- Simple Linear Deflection Function can improve prediction of processes that may be sensitive to small numbers of collisions.