SIMULATED RAREFIED ENTRY OF THE GALILEO PROBE INTO THE ATMOSPHERE OF JUPITER
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Simulated Rarefied Entry of the Galileo Probe into the Atmosphere of Jupiter

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Flow properties and aerodynamics are computed with a direct simulation Monte Carlo (DSMC) method for rarefied entry of the Galileo Probe into the atmosphere of Jupiter. Accurate predictions of vehicle drag coefficients are needed in order to assess atmospheric properties from the onboard Atmosphere Structure Experiment where highly-sensitive accelerometers will measure the drag force to within 10-6 bar during the initial entry phase at high altitudes. The corresponding flow rarefaction extends from the free molecule limit to the near continuum transition regime (Re<1000). Simulation results indicate that Co varies from 2.1 at the free molecule limit down to 1.6 at Re∞ = 1,000. Temperatures, densities, and internal energies throughout the flow field were also computed at each altitude ranging from 735 km to 353 km above the 1 bar level in the Jovian atmosphere. Surface heating and temperatures of the probe were computed directly in the DSMC code by assuming radiative equilibrium. Material response was re-assessed accurately during entry by accounting for conductivity, heat capacity, and pyrolysis which led to surface material mass efflux several times that of the freestream mass influx. The simulation also accounted for the quantum nature of the rotational energy mode of the dominant atmospheric species H2 through partial internal excitation in the freestream gas.

NOMENCLATURE

A  thermal accommodation coefficient
Co  drag coefficient
D  diameter
gj degeneracy of rotational quantum level j
j  rotational quantum level
k  Boltzmann constant, 1.3805 x 10^{-23} J/K
Kn  Knudsen Number
M  Mach number
q  net convective heat flux
Re  Reynolds number based on diameter
rj normalized rotational energy of level j
T  temperature
t  time during entry, starting at 735 km
Z  collision number for internal relaxation
α  VHS exponent of intermolecular potential
e  material radiative emissivity
ζr  rotational degrees of freedom
θ  characteristic mode temperature
μ  viscosity (kg/m²-s)
ρ  mass-density (kg/m³)
σ  Stefan-Boltzmann const., 5.67 x 10^{-8} W/(m²K⁴)

Subscripts:

o  deep-space value
ref  reference value
r  pertains to the rotational mode
v  pertains to the vibrational mode
w  value at wall or surface
∞  freestream value

INTRODUCTION

Just prior to encountering and orbiting Jupiter, the Galileo spacecraft will release a probe which will enter the Jovian atmosphere. During the initial aerobraking phase, the 45-degree blunted-cone probe will be protected from heating by a carbon phenolic shield. Once the probe velocity has been reduced from 47.5 km/s to 0.74 km/s, and entry heating has diminished, the probe will eject its heat shield and deploy a parachute. During descent, the probe will make several in situ measurements of atmospheric properties and transmit that data to the orbiting spacecraft. However, an Atmospheric Structure Experiment,1 similar to that employed in the Pioneer Venus mission, will also be on the Galileo probe to measure deceleration during the initial high-altitude entry phase. This experiment deduces atmospheric density, pressure, and temperature from deceleration measurements so long as the vehicle drag co-
efficient is known *a priori*. The instrument is sufficiently sensitive to detect any deceleration exceeding $10^{-5}$ m/s$^2$. Consequently, meaningful properties can be assessed for the Jovian upper atmosphere where the probe encounters highly rarefied flow during entry just prior to peak heating and ablation of the heat shield. This flow regime is bounded by the effective free molecule limit at 750 km altitude ($Re_\infty = 0.1$) and the near-continuum limit at 350 km ($Re_\infty = 1,000$). Note that since Jupiter has no identifiable surface, altitude is measured relative to the 1.0 bar pressure level in the Jovian atmosphere.

Accuracy of the experiment, however, depends upon the accuracy with which the probe drag coefficient is estimated. Intrieri$^2$ conducted a series of experiments in the ballistic range facilities at NASA Ames Research Center to measure the drag of several blunt-body configurations including the probes from Pioneer Venus and Galileo. Results for each were very similar, leading to values near $C_D = 1.1$ for $Re_\infty > 1,000$. However, $C_D$ rises significantly (approaching values near 2.0) for decreasing $Re_\infty$ below 1,000, although Intrieri’s experiments were not reliable in the rarefied regime. Furthermore, the experimental surface materials, gas species, and flow conditions (Mach number, density, etc.) differed significantly from those anticipated for the probe entry at a given Reynolds number.

Due to the lack of sufficient experimental data, the probe aerodynamics must be estimated computationally. Unfortunately, the flow regime is ill-suited to simulations which are based upon the continuum Navier-Stokes equations due to limitations in the constitutive relations for heat flux and shear stress. Instead, highly rarefied flows, for which the ratio of molecular mean free path to a body dimension is large (Knudsen number, $Kn > 0.10$), are best simulated computationally with direct simulation Monte Carlo (DSMC) particle methods.$^3,4$ Here, gas dynamics is modeled directly by the motion and interaction of thousands or millions of discrete particles. Particles which strike the vehicle may reflect back into the flow with velocities and internal energies corresponding to full or partial accommodation to the surface. The simulation permits accurate assessment of vehicle aerodynamics and heating along with properties of the flow field.

The objective of the present study was to assess the drag coefficient for the Galileo probe during entry from 750 km down to 350 km altitude in the Jovian atmosphere. Due to uncertainties in the applicable surface thermal accommodation coefficient $A$, simulations were repeated using different values to quantify its effects upon the vehicle entry. Surface heating was evaluated to determine the extent of pyrolysis of the heat shield through the use of the Charring Material Thermal Response and Ablation (CMA) program. This code models transient convective heating, radiation, in-depth conduction, heat capacity, and the flow of pyrolysiss gases through the porous material. Together, these codes simulate the entry environment and response of the Galileo probe to estimate the appropriate vehicle aerodynamics required for this and other aerobraking missions.

**SIMULATION MODELS**

The DSMC code employed in the present study was developed by Baganoff and McDonald$^4,5$ and enhanced for better application to rarefied aeropass maneuvers.$^6$ The flow field is divided into cubic cartesian cells to facilitate selection of colliding particles and sampling of macroscopic flow properties. The body geometry is modeled by a composite of planar facets in those cells through which the body surfaces pass. Each surface facet collects statistics regarding momentum and energy flux and may assume a surface temperature independent of neighboring facets. To simulate entry with the DSMC method, one must first specify properties of both gas-gas and gas-surface interactions.

**Gas-Gas Interaction Models**

Molecular interaction is simulated by the Variable Hard-Sphere (VHS) model of Bird$^7$ in which the collision outcome corresponds to isotropic scattering, akin to the mechanics of hard-sphere interactions. The collision rate, however, corresponds to an inverse power-law intermolecular potential of exponent $\alpha$. This parameter must be specified between the limits of the Maxwell molecule ($\alpha = 4$) and the Hard sphere ($\alpha = \infty$), and may be estimated from the known temperature dependence of gas viscosity $\mu$ as follows,

$$\frac{\mu}{\mu_{\text{ref}}} = \left(\frac{T}{T_{\text{ref}}}\right)^{\frac{1+\alpha}{\alpha}}. \quad (1)$$

Transport properties of the Jovian atmosphere, thought to be composed by a mixture of 89% H$_2$ and 11% He, were calculated from kinetic theory by Biolsi.$^8$ That work employed sophisticated semiempirical interaction potentials to solve the detailed collision integrals for viscosity, thermal conductivity, and binary diffusion for the gas mixture. Biolsi’s results for viscosity are plotted in Fig. 1 and compared to curves corresponding to the VHS model. The VHS parameters which yield best agreement in the figure and were employed in the current work are given by $\mu_{\text{ref}} = 2.24 \times 10^{-5}$ kg/m-s, $T_{\text{ref}} = 1000$ K, and $\alpha = 10.5$.

Of additional concern in gas-gas interactions is the inelastic exchange of molecular energies due to relaxation of the internal energy modes for rotation and vibration. The mechanics of these exchange processes are modeled in the DSMC code by the methods of Borgnakke and Larsen$^9$ and Haas, *et al.*$^{10}$ These involve partitioning post-collision thermal energies in a manner which corresponds to equilibrium
The rates of rotational and vibrational relaxation are dictated by collision numbers $Z_r$ and $Z_v$, respectively. Solutions of the master equation using state-to-state transition probabilities estimated from quasi-classical methods\textsuperscript{11–13} have led to rotational relaxation rates in H$_2$ described by $Z_r = 100$. Simple application of the Millikan and White\textsuperscript{14} empirical expression for vibrational relaxation rates suggests that $Z_v$ is several orders of magnitude larger than $Z_r$, leading to exceedingly slow vibrational excitation. Furthermore, given the high characteristic temperature of vibration ($\Theta_v = 6320$ K)\textsuperscript{15} for H$_2$, it is unlikely that the vibrational mode will contribute significantly to the thermodynamics of this flow and was therefore neglected in the present work.

DSMC methods typically model molecular rotation as a continuous energy mode with two degrees of freedom, $\zeta_r = 2$. However, at freestream conditions, the quantized nature of the rotational mode for H$_2$ leads to an effective number of degrees of freedom below two as a result of its high characteristic temperature ($\Theta_r = 85.33$ K).\textsuperscript{15} As plotted in Fig. 2, dependence of $\zeta_r$ upon temperature $T$ is described by the rotational partition function and may be expressed as follows,

$$\zeta_r = 2 \sum_j g_j r_j \exp \left(-r_j \right) \sum_j g_j \exp \left(-r_j \right)$$

where the normalized energy $r_j$ and degeneracy $g_j$ per rotational quantum level $j$ are defined as follows:\textsuperscript{16}

$$r_j = j(j + 1) \frac{\Theta_r}{kT},$$

$$g_j = 2j + 1.$$  

Here, $q$ is the net convected heat flux to each facet accounting for both incident and reflected energy. As will be described later, this model can be enhanced to account for material heat capacity, thermal conductivity through the heat shield, and pyrolysis of the surface material.

Definitive values for $A$ and $\varepsilon$ for the interaction of Jovian atmospheric gases upon carbon phenolic material at flight conditions are not readily available. As used in the this study, a surface emissivity of $\varepsilon = 0.85$ was suggested by Bueche\textsuperscript{19} from ground-based experiments, flight data, and theoretical predictions, and is at least consistent with estimates cited elsewhere.\textsuperscript{20–23} Appropriate values for $A$ may be found with even less certainty than $\varepsilon$ from limited related experimental data\textsuperscript{24} and theoretical\textsuperscript{25} results. It therefore proved necessary to repeat simulations using different values of $A$ to assess sensitivity of the results to this parameter.

**SIMULATION RESULTS**

The DSMC code was used to simulate entry of the Galileo probe at several points along its trajectory from 735 km altitude to 353 km. Table 1 lists the simulation conditions for each case with atmospheric data taken from Orton. Note that this time is measured relative to the 735 km trajectory point. For all cases the velocity was assumed to be 47,450 m/s and the Knudsen number and Reynolds number were based on the probe diameter (1.265 m). The grid resolution employed in the present work is defined in Table 1 by the size of the probe diameter measured in cell-lengths, and was sufficiently fine to yield less than 1% error in drag and heating.\textsuperscript{26} The geometry of the probe is compared to the simulation models in Fig. 3. Note that only one quadrant of
the probe was simulated, taking advantage of two planes of
symmetry of the body.

In general, flows with greater \( \text{Re}_{\infty} \) require greater re-
solution in order to resolve flow gradients and avoid over-
predicting drag and heat transfer. However, the required
size of the flow domain increases with lower \( \text{Re}_{\infty} \) because
molecules which reflected from the probe surface are capa-
bable of diffusing far into the flow when collisions are scarce.

The extent of the upstream diffusion of particles is depicted
in the plot of flow temperature along the stagnation stream-
line in Fig. 4. The upstream domain boundary for each sim-
ulation case was sufficiently far upstream that the transla-
tional temperature was near its freestream value to prevent
overprediction of heat transfer and drag. Density profiles
along the stagnation streamline are plotted in Fig. 5 and also
exhibit the effects of rarefaction. Note that no clear shock
structure is observed since the shock is fully merged with
the body layer. Density rose considerably near the body
surface due to particle reflection from the relatively cold

For each case, the simulation employed at least 16 par-
ticles per cell in the freestream and roughly 3 to 7 mil-
mion particles total. The code was optimized for vector-
processing on Cray supercomputers, requiring roughly
0.6 \( \mu \text{s} \)/particle/timestep on the Cray C-90 or a total run
time of 5,000-8,000 CPU seconds depending upon the case.
Memory requirements ranged from 50 to 200 megawords.

Results of each case, identified by \( \text{Re}_{\infty} \), are presented
in Table 2. The cases were run with \( A = 0.75 \) and several
were repeated with \( A = \{0.5, 0.9\} \). Heating of the nose re-

region was highly sensitive to accommodation coefficient \( A \)
while drag was fairly insensitive, particularly for the high-
est and lowest \( \text{Re}_{\infty} \) cases. Simulated drag coefficients
for the Galileo probe are plotted in Fig. 6 and compared to the
experimental ballistic range results of Intrieri for spheres
and the Pioneer Venus probe. Unfortunately, Intrieri’s re-
gults for the Galileo probe were all at high angles of attack
and were of questionable quality at low \( \text{Re}_{\infty} \).

In general, drag dropped with increasing \( \text{Re}_{\infty} \) above 10,
but did not appear to blend well with the high-\( \text{Re}_{\infty} \) exper-
imental data. However, the experiments were performed at
lower Mach numbers (roughly \( M_{\infty} = 14.5 \)) in \( \text{CO}_2 \) com-
pared with the high Mach numbers expected for Galileo en-
try in the \( \text{H}_2-\text{He} \) Jovian atmosphere. Indeed, for comparing
highly rarefied flows, a suitable parameter for correlating
the data would be the Knudsen number \( \text{Kn}_{\infty} \). Re-plotting
the data in Fig. 7 suggests a smoother transition between
the simulation results and the experimental work.

Nonetheless, it was instructive to simulate a few of In-
trieri’s experiments for more direct comparison. Spheres
flying at roughly \( M_{\infty} = 14.5 \) in pure \( \text{CO}_2 \) for \( \text{Re}_{\infty} = \{192, 4564\} \) were simulated with the DSMC code employ-
ing the same surface description as above. The results are
included in the drag plots and appear to follow the experi-
mental trends quite well. Additional simulations will be
performed to reproduce the Pioneer Venus probe experi-
ments and results will be reported in the final paper.

Surface Temperatures and Pyrolysis

The DSMC calculations above employed a radiative-
equilibrium energy balance to compute the surface tem-
perature. This boundary condition neglects any effects of
heat capacitance and heat conduction in the spacecraft heat
shield and, therefore, provides an upper bound for the sur-
face temperature. The calculations also neglected pyrolysis
from the heat shield which can be significant for a high-
energy incident flow at very low densities.

To check the validity and accuracy of these assump-
tions, the CMA code\cite{27,28} was used to calculate the one-
dimensional heat transfer into the carbon phenolic heat
shield at the stagnation point. Temperature-dependent ma-
terial properties, surface re-radiation, and in-depth pyro-
lysis were included in the calculation, but surface ablation
was neglected. The initial temperature was estimated to be
150 K just prior to entry from deep space. The aero-
thermal heat flux was taken from the DSMC results associated
with \( A = 0.75 \) appearing in Table 2.

Figure 8 presents the transient surface temperature at
the stagnation point during Galileo entry. As expected, the
CMA-calculated surface temperature is always below the
radiative-equilibrium temperature. The temperature differ-
ence between the two results increases from about 200 K
at the initial time (\( \text{Re}_{\infty} = 0.098 \)) to 1130 K at 55 seconds
(\( \text{Re}_{\infty} = 926 \)).

Figure 9 compares the stagnation point pyrolysis-gas
mass flux with the free stream mass flux. The pyrolysis gas
mass flux becomes significant between 43 and 48 seconds as the
material temperature rises from 600 K to 1000 K. At 46.4
seconds (\( \text{Re}=103.4 \)) the pyrolysis gas flux is more than 20
times the free stream mass flux.

Perhaps the drag coefficient does not depend strongly on
the surface temperature which can itself be significantly be-
low the radiative equilibrium value during entry. However,
the surface mass flux due to pyrolysis of the material is sig-
ificant once the probe drops below roughly 420 km. This
could lead to a noticeable increase in drag and a decrease in
heating. Thorough simulation requires that this mass flux
be coupled directly into the DSMC code. Such modifica-
tions are underway and the results will be reported in the
final paper.

Concluding Remarks

Drag on the Galileo probe during initial entry into the
Jovian atmosphere was computed with a DSMC method,
and the results were consistent with the experimental re-
Acknowledgements

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References


### Table 1: Galileo Probe Entry Simulation Conditions

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<th>Alt. (km)</th>
<th>Re</th>
<th>M</th>
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### Table 2: Galileo Probe Entry Simulation Results

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Fig. 1 Temperature variation of viscosity of the Jovian atmospheric gas mixture computed by Biolsi and fit with the VHS model.

Fig. 2 Temperature dependence of the rotational degrees of freedom for H₂.

Fig. 3 Comparisons of probe geometry to simulation configurations employing differing resolutions.

Fig. 4 Translational temperature along the stagnation streamline ahead of the probe for entry at several values of Re₉₉.

Fig. 5 Mass density along the stagnation streamline ahead of the probe for entry at several values of Re₉₉.

Fig. 6 Drag coefficients from DSMC simulation of Galileo entry compared to results of related experiments of Intrieri; includes results from simulations of sphere experiments. Results plotted against Re₉₉.
Fig. 7 Drag coefficients from DSMC simulation of Galileo entry compared to results of related experiments of Intriere; includes results from simulations of sphere experiments. Results plotted against $\text{Kn}_{\infty}$.

Fig. 8 Radiative-equilibrium and CMA-calculated stagnation point material temperature for initial entry period of the Galileo probe.

Fig. 9 Comparison of freestream mass flux and CMA-calculated pyrolysis gas mass efflux from the probe surface during initial entry phase.