Accelerating DSMC Simulations of Micrometeoroid Entry using a Gaussian Process Surrogate

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Motivating Problem

The entry of micrometeoroids into the atmosphere is a complex physical process, which includes ablation, rarefied hypersonic flow, and plasma formation. The models that correlate radar data to micrometeoroid and atmospheric properties are based on simplifying assumptions (e.g. isothermality) which may not always be applicable [1]. This inherent complexity motivates first-principle computational studies aimed at simultaneously capturing these coupled physical processes.

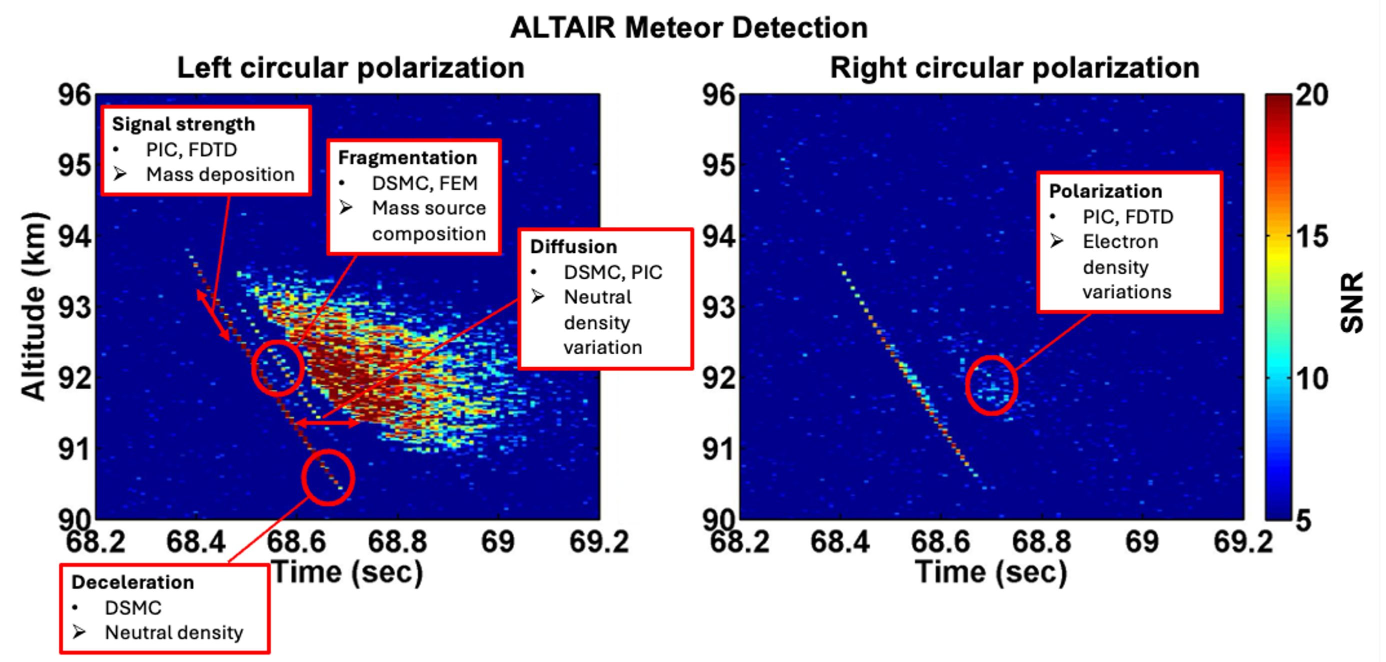


Figure 1. Representative RTI image of a meteor observed at ALTAIR, showing (left) left-circular polarization and (right) right-circular polarization with annotated phenomena and relevant simulation methodologies to extract measurements of atmospheric parameters.

Objective 1: Formulate micrometeoroid entry as a fluid-structure-thermal interaction problem in rarefied flow and conduct coupled DSMC-FEM simulations

Objective 2: Develop a framework for accelerating these solutions using a GP surrogate model

Problem Setup & Coupling Strategy

Physics	Governing Equation	Method/Software
Structural Dynamics	$\rho\frac{\partial^2 \mathbf{x}_s}{\partial t^2} - \nabla \cdot \sigma_s = \mathbf{b}$	Finite Element Method (FEM)/ AERO-S
Thermal Dynamics	$\rho c_p \frac{\partial T_s}{\partial t} - \nabla \cdot (k \nabla T_s) = \dot{q}$	FEM / AERO-S
Fluid Dynamics	$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t}\right)_c$	DSMC / SPARTA

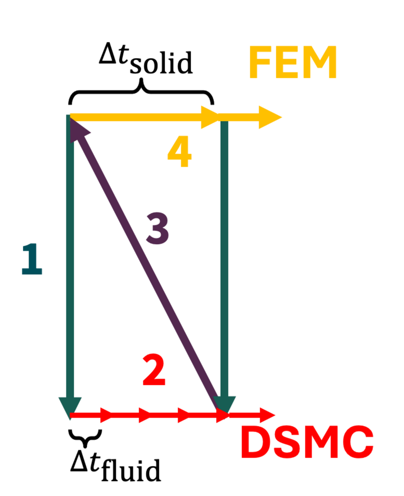


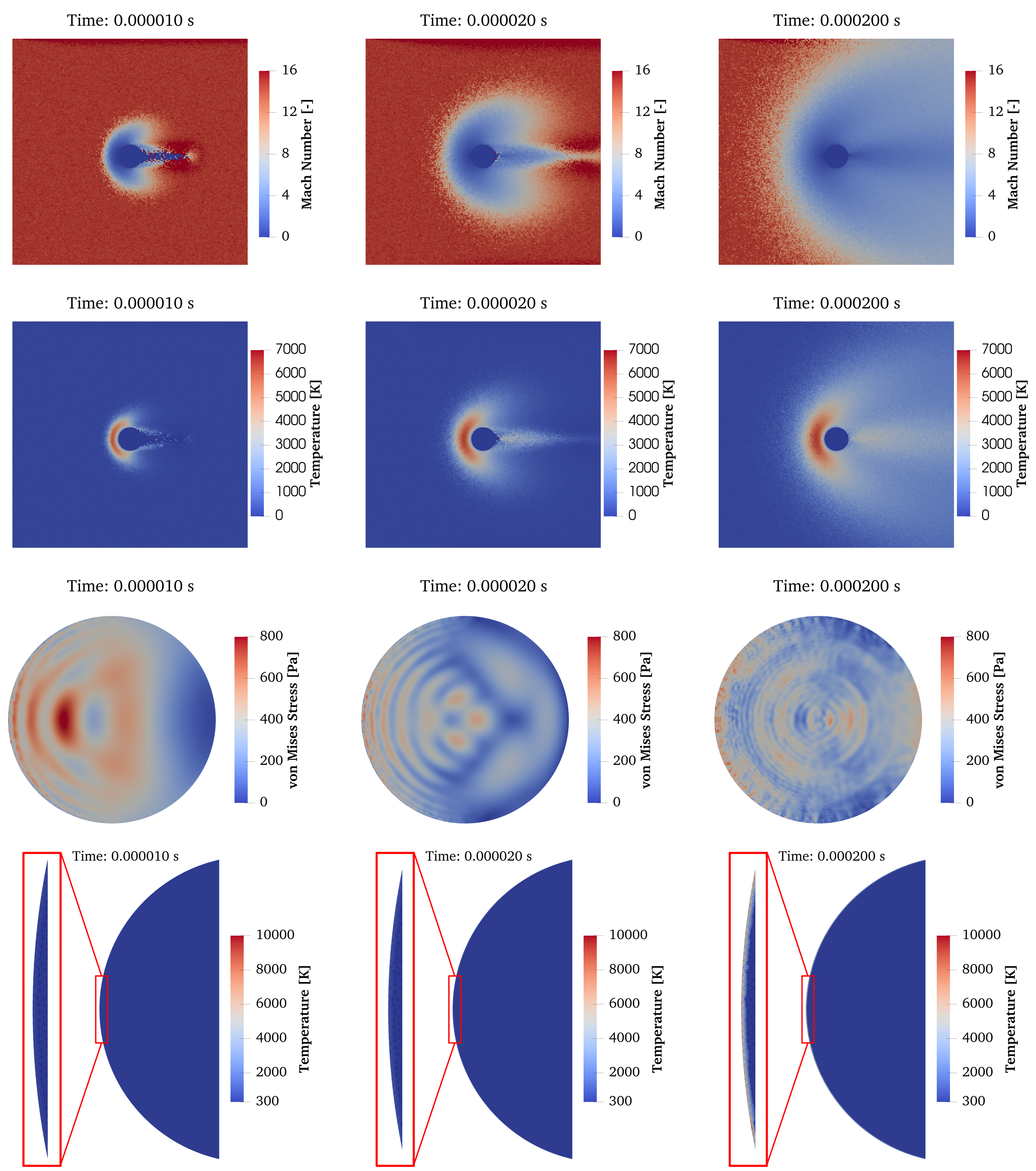
Figure 2. Partitioned Coupling

DSMC-FEM Coupling

1. FEM sends displacements/temperature to DSMC.
2. DSMC computes forces/heat flux using updated displacements/temperatures.
3. DSMC sends forces/heat fluxes to FEM.
4. FEM uses forces/heat fluxes from DSMC as Neumann boundary conditions to solve for new displacements/temperatures.

Flow Properties (Air at 90 km)			
Mach	15	Kn	0.8
T_∞	200 K	ρ_∞	3.4×10^{-6} kg/m^3
Material Properties (Stone Meteoroid)[2]			
E	15 GPa	ν	0.3
ρ_s	3000 kg/m^3	k	3 W/(m·K)
c_p	1000 J/(kg·K)	T_0	300 K
Numerics			
DSMC Cells	5×10^4	Δt_f	10^{-8} s
Elements	3×10^4	Δt_s	10^{-6} s
No. Particles	1.7×10^7	Total time	500 ms
No. cores	480	Clock time	22 min
Boundary Condition			
Left	Inflow	Top/Bot/Right	Outflow
Gas-Surface	Diffuse	Accommodation	1.0

DSMC-FEM Results



Results & Discussion

This work presents the **first high-fidelity coupled simulation of rarefied fluid–structure–thermal interaction using DSMC and FEM solvers**. We simulate the flow field, and the structural and thermal response of a micrometeoroid entering Earth's atmosphere at Mach 15 and 90 km altitude. The results capture the formation of the characteristic bow shock ahead of the micrometeoroid and the buildup of stress within the windward region of the body. The flowfield reaches steady state after approximately 200 ms. Significant heating is observed only on the flow-facing surface, while the interior temperature remains largely unchanged. This is due to significant timescale differences between the fluid and the structure. **This capability enables highly accurate multiphysics simulations** by leveraging the strengths of both DSMC and FEM; however, the timescale disparity between the fluid and structural-thermal domains motivates the development of surrogate models to **accelerate these simulations while maintaining predictive accuracy**.

Gaussian Process Surrogate

To accelerate coupled DSMC–FEM simulations, we represent the particle velocity distribution function, f, using a low-order approximation and learn the parameters of this representation as functions of the global flow and local surface conditions, μ. Specifically, we approximate the surface distribution function using a **Hermite spectral expansion about a local Maxwellian**,

$$f_{\text{surf}}(\mathbf{v};\boldsymbol{\mu}) = f_M\left(\mathbf{v};\mathbf{u}(\boldsymbol{\mu}),T(\boldsymbol{\mu})\right)\left[\sum_{k=0}^{n}\sum_{l=0}^{n}\sum_{m=0}^{n} a_{klm}(\boldsymbol{\mu})\psi_k\psi_l\psi_m\right].$$

The expansion coefficients, a_{klm}, characterize departures from equilibrium and are obtained from

$$a_{klm}^{[\alpha]} = \frac{1}{k!l!m!}\alpha^{-k-l-m}\int_{-\infty}^{\infty} f(\mathbf{v};\boldsymbol{\mu})\psi_k\psi_l\psi_m d\mathbf{v}$$

A Gaussian process surrogate will be trained to predict the coefficients $a_{klm}(\mu)$), enabling rapid reconstruction of the distribution function and its moments, from which surface fluxes are evaluated, without performing a DSMC simulation.

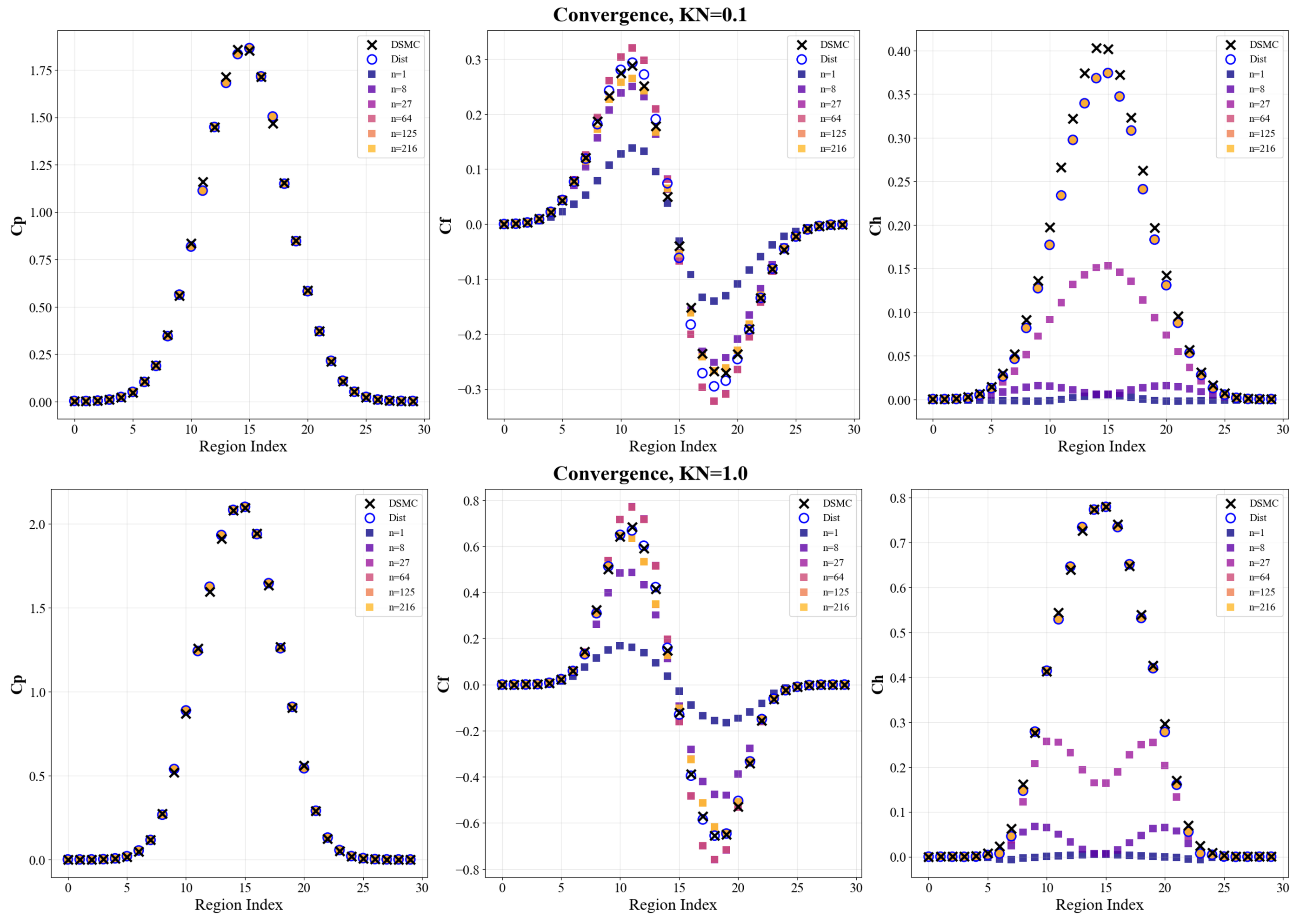


Figure 3. Validation of the Hermite spectral expansion for representing surface fluxes in a Mach 10 argon flow over a 12-in. cylinder at Kn = 0.1 and 1.0[3]. Surface quantities are evaluated at 30 angularly uniform locations around the cylinder. Shown are the coefficient of pressure ((C_p), left), coefficient of shear stress ((C_f), center), and coefficient of heat flux ((C_h), right). Results obtained directly from DSMC particle statistics are compared with values computed from sampled VDF histograms and from the corresponding Hermite spectral expansion. The agreement between the DSMC, histogram-based (Dist), and Hermite-based fluxes demonstrates that the low-order expansion faithfully represents the underlying velocity distribution function and preserves the surface quantities of interest.

Conclusion & Next Steps

We have demonstrated the first high-fidelity coupled DSMC–FEM simulations of rarefied fluid–structure–thermal interaction and validated a low-order Hermite representation for accelerating these simulations. The results show that the reduced-order model accurately captures the velocity distribution function and resulting surface fluxes, providing a foundation for Gaussian process surrogate modeling. Future work will focus on validating and deploying these surrogate models in realistic applications, enabling faster yet accurate multiphysics simulations for problems such as micrometeoroid entry, high-altitude hypersonic flight, and MEMS devices.

[1] T. Hedges et al. *Investigating Rotation and Anisotropic Ablation of Small Meteoroids and their Effects on Head Echo Plasma Formation via Computational Techniques*. en. 2025. (Visited on 06/20/2025).
[2] G. J. Flynn et al. "Physical properties of the stone meteorites: Implications for the properties of their parent bodies". en. In: *Geochemistry* 78.3 (2018), pp. 269–298. (Visited on 10/18/2024).
[3] M.-C. Lo et al. "Development of parallel direct simulation Monte Carlo method using a cut-cell Cartesian grid on a single graphics processor". en. In: *Computers & Fluids* 101 (2014), pp. 114–125. (Visited on 02/07/2026).

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