

Estimating meteoroid trajectories in Earth's atmosphere using an ablation model

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Introduction

- Each year an estimated 25 million meteoroids enter Earth's atmosphere.
 - Most meteoroids have a mass of 1 milligram or smaller, and they enter the atmosphere at speeds of up to 72 km/sec.
- These high velocity particles have the **potential to damage spacecraft** by causing surface degradation.
 - Craters are formed** upon impact with spacecraft, which can cause **immediate damage** to functional surfaces such as solar panels or optical surfaces like telescope lenses.
- Modeling meteoroids in Earth's atmosphere can help **assess the risk associated with surface degradation** and other forms of damage to spacecraft caused by meteoroid impacts.
- An ablation model, a series of equations that **describe changes in a meteoroid's physical properties** in Earth's atmosphere, can be used to **estimate the trajectory of meteoroids** with an initial mass of a microgram or smaller.
 - The model consists of 4 coupled differential equations which describe a meteor's **change in altitude, velocity, mass, and temperature** with respect to time.
 - The model cannot accurately simulate meteoroids with an initial mass too great because of their tendency to fracture into smaller meteoroids, which the model does not account for.

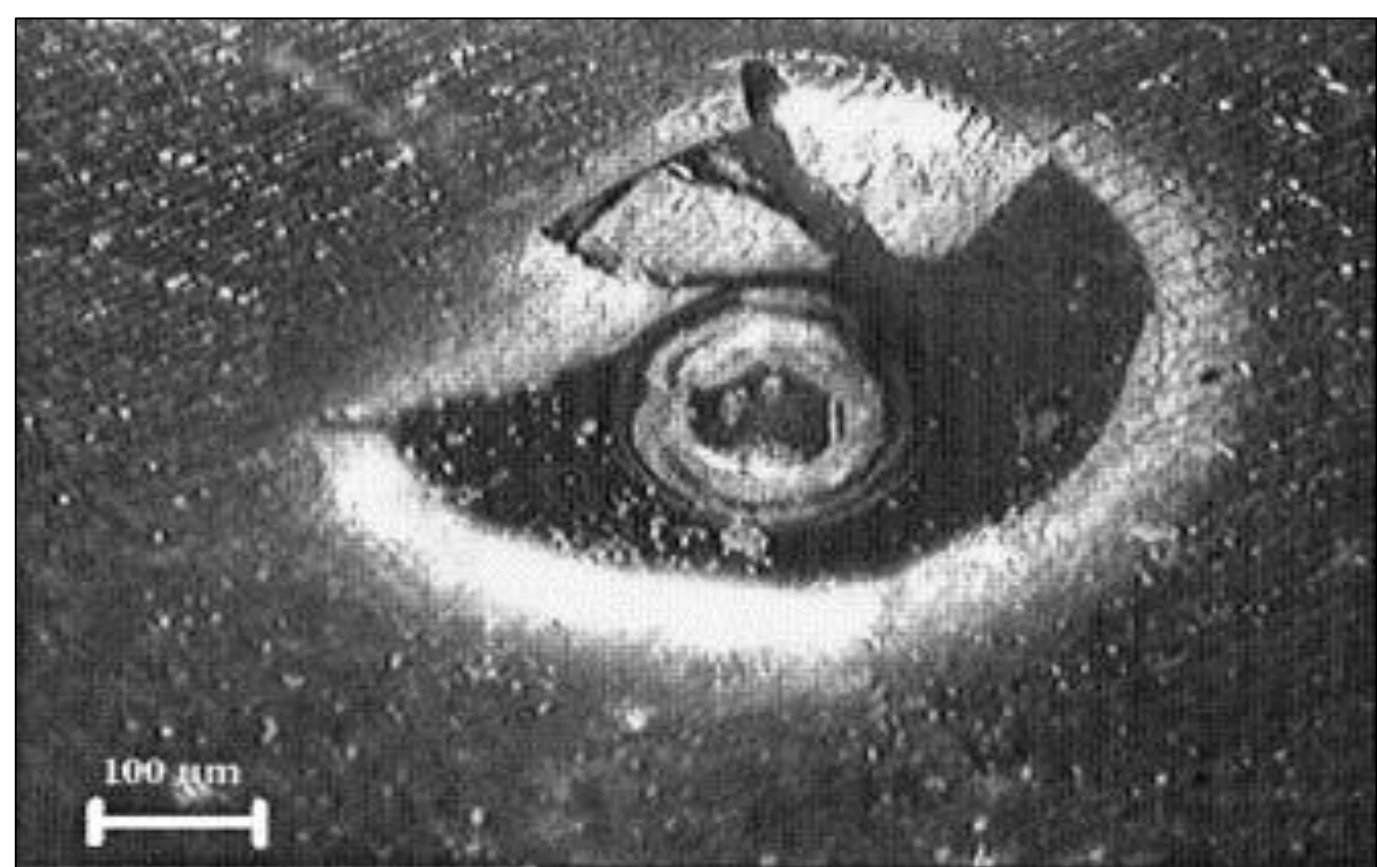


Image of micrometer-sized impact on the MLI of Hubble Space Telescope's solar array boom. The external diameter is 0.0005 meters. Image credit Landgraf, Hazards by Meteoroid Impacts onto Operational Spacecraft, 2004.

Results

Figures 2-4 use a variety of input parameters to demonstrate the effects that changing certain meteoroid properties has on the diameter of the resulting impact crater.

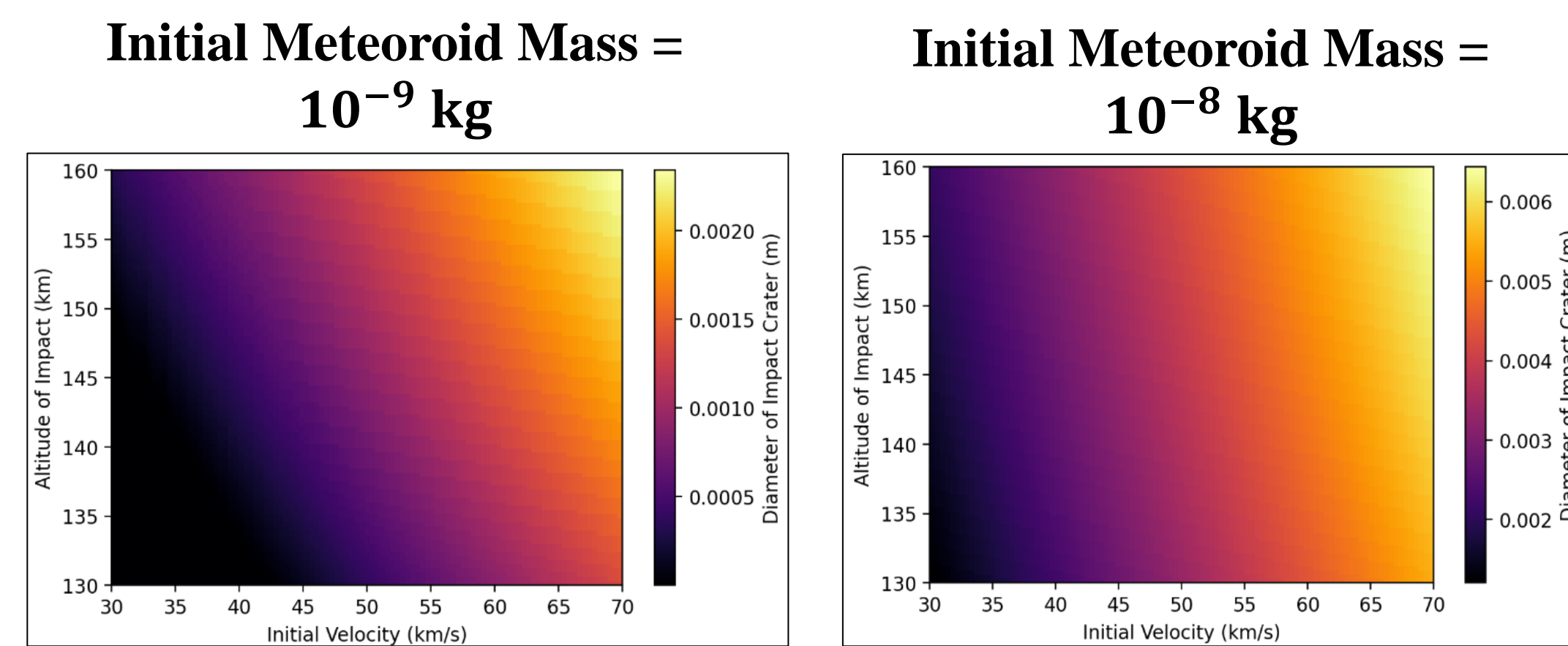


Figure 2 (Above): The diameter of the impact craters resulting from collision with the particles in a range of altitudes from 130-160 kilometers. The left map assumes the initial particle mass is 1×10^{-9} kg and the right map assumes 1×10^{-8} kg.

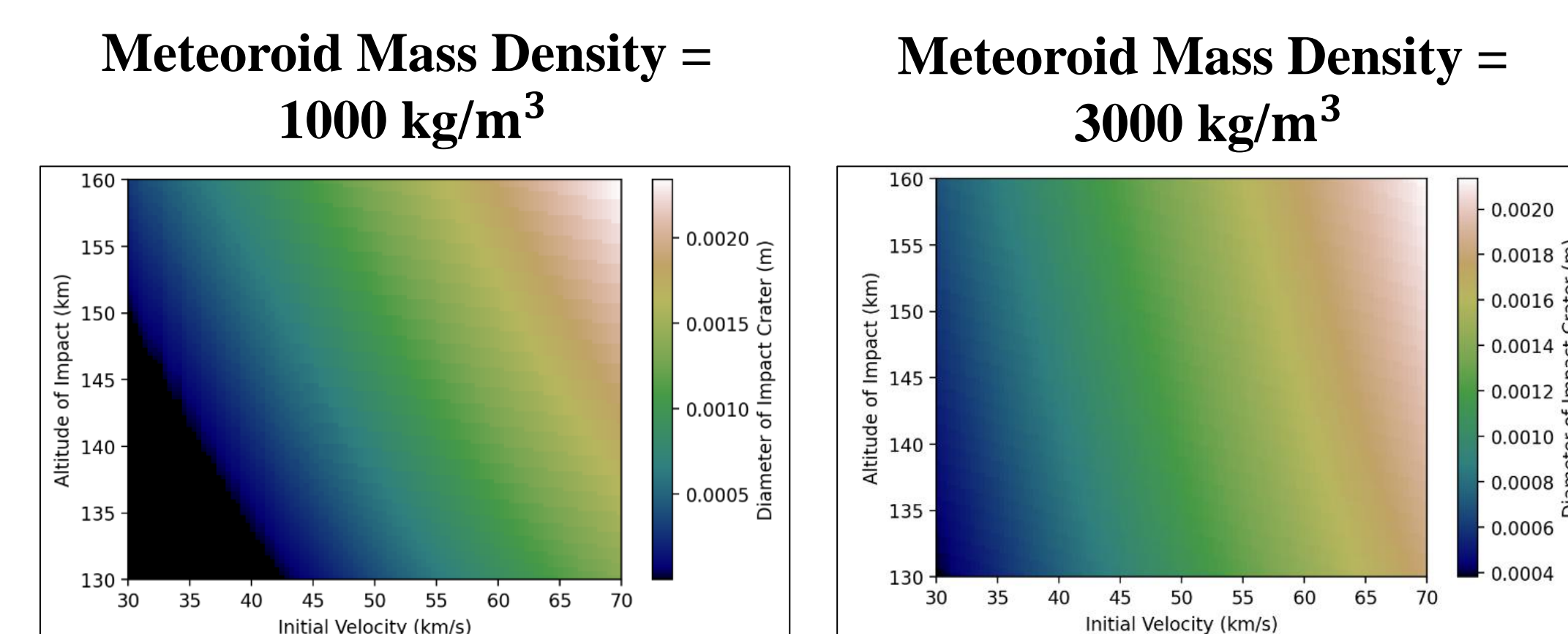


Figure 3 (Above): The diameter of the impact craters resulting from collision with the particles in a range of altitudes from 130-160 kilometers. The left map assumes the particle density is 1000 kg/m^3 and the right map assumes 3000 kg/m^3 .

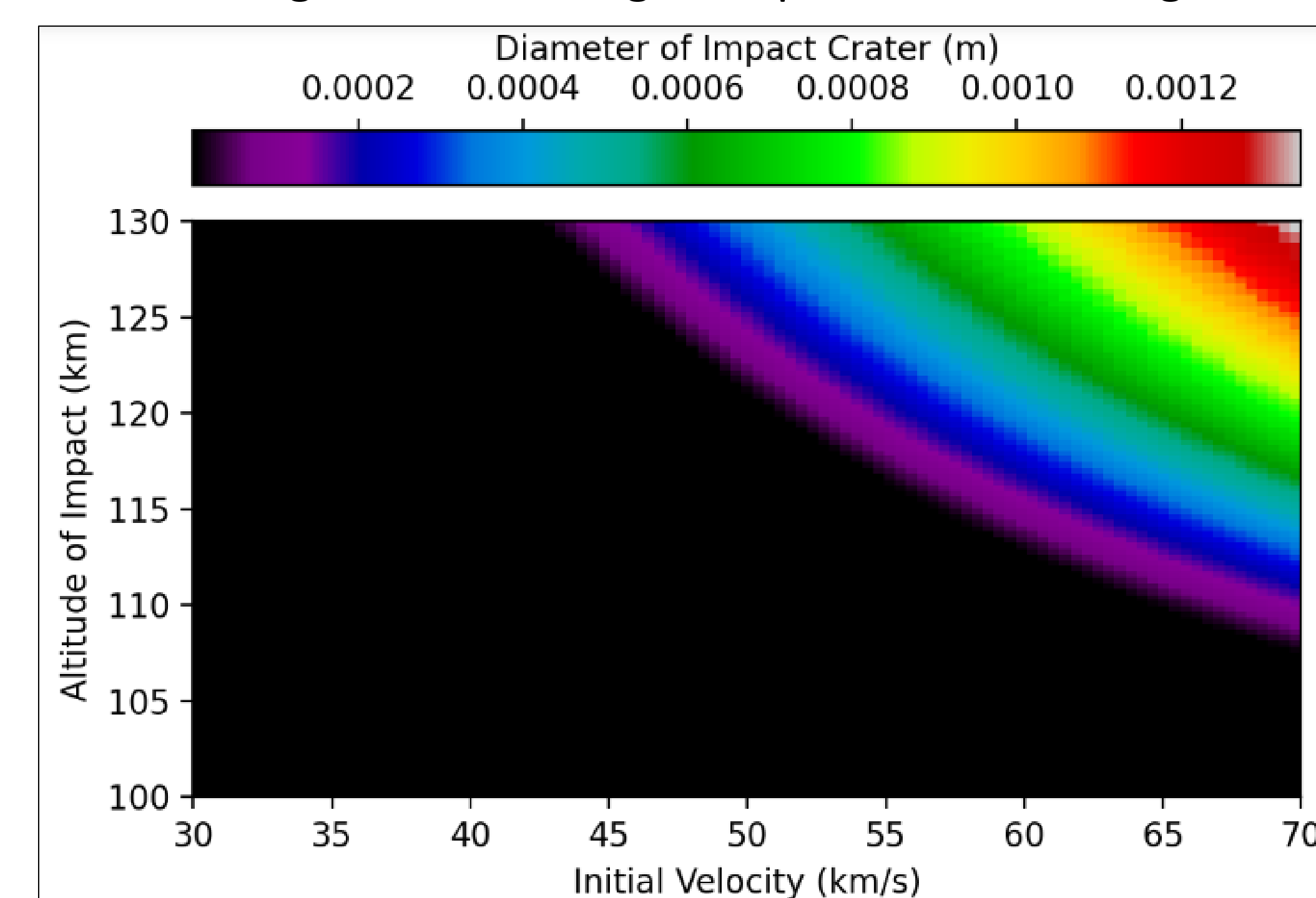


Figure 4 (Above): The color map demonstrates the diameter of the impact craters resulting from collision with the particles in a range of altitudes from 100-120 kilometers. The results assume an initial particle mass of 1×10^{-9} kg and a density of 1000 kg/m^3 .

Conclusions

- Figure 3 demonstrates how the **initial meteoroid mass greatly impacts the size of the surface degradation** at all tested altitudes.
 - With the range of this property being so large, it makes it very difficult to draw any general conclusions about the impact crater diameter without an accurate initial mass.
- The meteoroid mass density, however, seemed to have **less of a substantial impact on the impact crater**. The largest diameter when increasing the density by a factor of 3 seems to have not changed to any significant degree.
 - Although the size of the impact crater for the higher altitudes remained almost unchanged, it can be observed that the higher density did **marginally increase the diameter of the impact craters at lower altitudes**, especially for lower initial velocities.
 - The variation in density is also significantly lower than the variation in initial meteoroid mass, meaning that if an assumption was made for the value of the density the results likely would not be substantially impacted.
- Figure 5 demonstrates that as the mass of the meteoroid shrinks to a certain point, the impact crater quickly reaches arbitrary levels of size. In actuality, **the particle would eventually ablate completely and leave no crater**.
- In the future, the accuracy of the simulations could be determined by comparing the estimations of the particle's mass and speed at the time of impact with data observed by actual meteoroids. Doing this would allow **the margin of error for the diameter of the impact crater** to be accounted for in the simulations.

References

- Elizabeth., Determining meteoroid properties using head echo observations from the Jicamarca Radio Observatory <https://open.bu.edu/handle/2144/32016>.
- Landgraf, M.; Jehn, R.; Flury, W.; Dikarev, V. Hazards by Meteoroid Impacts onto Operational Spacecraft. Advances in Space Research 2004, 33 (9), 1507–1510. <https://doi.org/10.1016/j.asr.2003.06.001>.
- McBride, N.; McDonnell, J. a.m. Meteoroid Impacts on Spacecraft:: Sporadics, Streams, and the 1999 Leonids. Planetary and Space Science 1999, 47, 1005–1013. [https://doi.org/https://doi.org/10.1016/S0032-0633\(99\)00023-9](https://doi.org/https://doi.org/10.1016/S0032-0633(99)00023-9).

Methods

- The **size of the particle and the particle's speed at the time of impact** need to be known to calculate the measurements of the surface degradation on the spacecraft.
- We wrote Python code to create a **simulation of the meteoroids** and their physical properties using the ablation model.
 - Using the estimations of mass and velocity given from the Python simulations, we had a way to **estimate surface degradation**.

(Right) Chart of parameters for the ablation model equations used in the simulations.

Parameter	Description	Value
A	shape factor	1.21
C ₁	Clausius-Clapeyron coefficient	$6.92 \times 10^{11} \text{ kg/m}^2/\text{s}$
C ₂	Clausius-Clapeyron coefficient	$5.78 \times 10^4 \text{ K}$
r	drag coefficient	1.0
Q	energy of evaporation of 1 kg material	$6 \times 10^6 \text{ J/kg}$
c	specific heat of meteoroid	1000 J/K
Λ	heat transfer coefficient	1.0
σ	Stefan-Boltzmann constant	$5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$
L	latent heat of fusion plus vaporization	$6.0 \times 10^6 \text{ J/kg}$
ρ _m	meteoroid mass density	1000 kg/m^3
v	meteoroid velocity	
ρ _{air}	atmospheric air density	
T	meteoroid temperature	
T _a	atmospheric air temperature	
m	meteoroid mass	
χ	zenith angle	
Λ _s	sputtering coefficient	

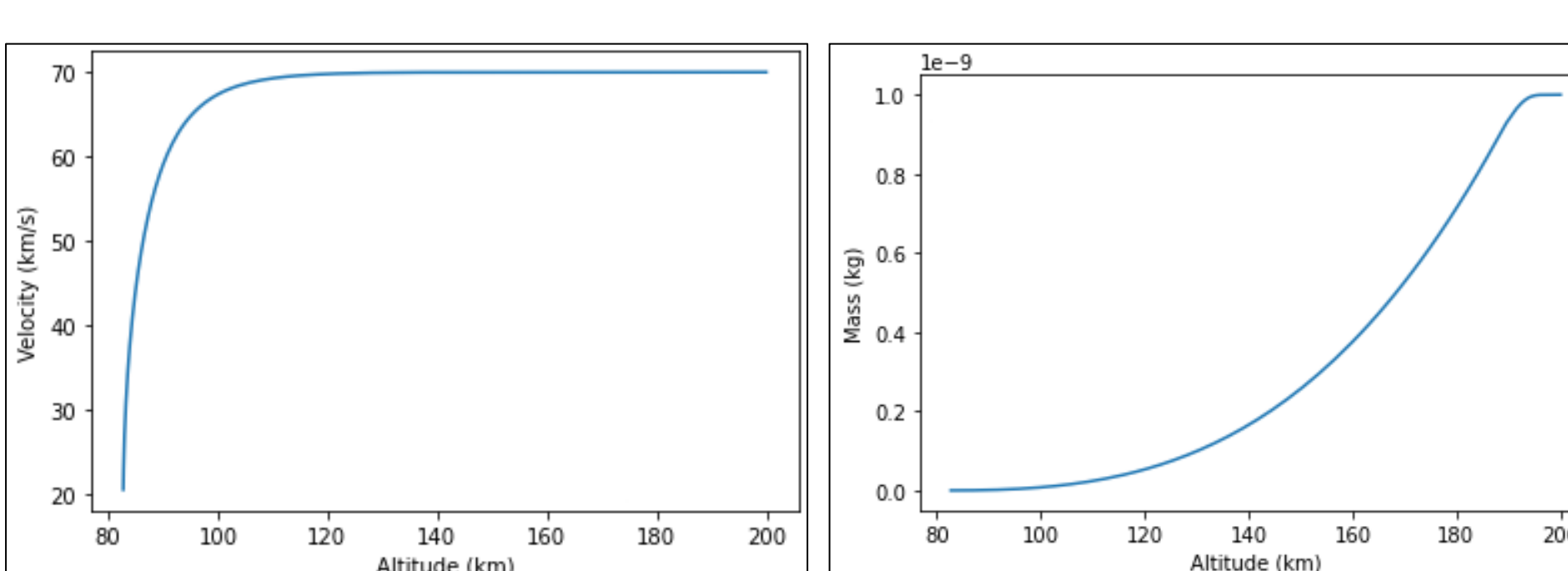


Figure 1: Example of velocity and mass estimations produced by code. Simulations assume an initial altitude of 200 km, initial velocity of 70 km/s, and initial mass of 1×10^{-9} kg.

The ablation model used for the simulation is composed of these four equations.

$$\frac{dh}{dt} = -v \cos(\chi) \quad \frac{dv}{dt} = \frac{-\gamma A \rho_{air} v^2}{m^{1/3} \rho_m^{2/3}}$$

$$\frac{dm}{dt} = \frac{-4Am^{2/3}C_1}{\rho_m^{2/3}T^{1/2}} \exp\left(-\frac{C_2}{T}\right) - \frac{\Lambda_s Am^{2/3} \rho_{air} v^3}{2Q\rho_m^{2/3}}$$

$$\frac{cm^{1/3} \rho_m^{1/3}}{A} \frac{dT}{dt} = \frac{1}{2} \Lambda \rho_{air} v^3 - 4\sigma(T^4 - T_a^4) + \frac{L}{A} \left(\frac{\rho_m}{m}\right)^{2/3} \frac{dm}{dt}$$

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