# A Simulation-based Study of the Meteorite that Created the Sudbury Basin

**Topic**: Physics

**Research Question**: How do the properties of a meteorite including its radius and mass affect its kinetic energy when it impacts the surface of the Earth?

**Word Count** : 3991

# Contents

# 1 Introduction

Over 1.8 billion years ago, a meteorite struck the surface of the Earth in Northern Ontario creating the Sudbury basin; the second largest impact crater on Earth. This meteorite is theorized to have deposited many of the materials that drive the city's mining-based economy today including nickel and copper. My exposure to this city prompted strong interests in both the meteorite impact and the meteorite itself which are explored in this investigation. This study attempts to calculate different physical properties of a meteorite at the moment of impact by simulating its flight and eventual collision with the Earth. Namely, I look at final velocity, final mass, final radius and kinetic energy. I hope that measuring these quantities will allow me to better understand how a meteorite changes during its flight and how basins like Sudbury are created.

Modelling the movement of a meteorite through a fluid requires that I consider a number of physical laws spanning many different disciplines. These topics, which include thermal physics and mechanics, have different degrees of impact on the flight of a meteorite. The laws in each of these fields can be modelled with an infinite degree of complexity. For the purposes of this study, I restrict the complexity of the simulation by only including features that I believe will have a significant impact on the nature of the results. Gravitation, for example, is a key concept that must be considered in order to understand the movement of a meteorite as it nears a planet. A simple implementation may consider gravitational acceleration to be constant whereas in a more accurate simulation acceleration due to gravity may be represented as a function of the meteorite's distance from the Earth. By better approximating each component, simulations can be built-out from broad abstractions to increasingly accurate models.

In this investigation, I create a simulation to model the aforementioned properties of the meteorite similar to the one that created the Sudbury basin as it enters the Earth's atmosphere and eventually collides with its surface. In the first step, I create a base simulation that only incorporates the most important variables (including gravity and drag) in a simplistic manner. The final simulation implements more features and refines the crudely approximated features introduced in the base simulation. I then use the completed simulation to model the impact in Sudbury using publicly available data to encode the features of the meteorite.

# 2 Background

## 2.1 Classification of Meteorites

A piece of space debris ranging in size from a speck of dust to a more sizable chuck of rock is broadly defined as a meteoroid. This definition on its own is inherently vague. It is much more useful as a hierarchical distinction (i.e. an asteroid is larger than a meteoroid). This classification develops two further distinctions after a meteoroid has entered the atmosphere of a planet: meteorites and meteors. Meteors burn up in a planet's atmosphere before reaching the surface as a result of the intense friction with the air they are subjected to during their flight. A meteorite, on the other hand, survives its flight through the atmosphere and makes contact with the surface of a planet while still intact. It is also accurate to call a very large body an asteroid after it has entered a planet's atmosphere but I use meteorite here because our simulation can be applied to meteors of all sizes.

Further classification of meteorites is largely based on their mineralogical and petrographic characteristics. The Weisberg et al. (2006) scheme [1] groups meteorites into three distinct groups: chondrites, primitive achondrites, and achondrites. For the purposes of this study, I classify the meteorite solely based on qualitative observed data relating to its composition. Classifying the meteorite, even broadly, allowed me to estimate its mass which is a necessary component of my calculations. Based on the materials the meteorite discharged around the Sudbury area, I believe the meteorite to be mostly made of taenite; an iron nickel alloy that has a ratio of nickel and iron similar to that of the Sudbury area basin. Taenite can be up to 65% nickel by mass and the Sudbury basin has a greater proportion of nickel than iron. I further classify the meteorite as an achrondite because a lack of silicon in the basin makes it unfit for the other two categories.

The radius of the meteorite is estimated to be between 5000 and 8000 meters by the Lakehead Conservation Region [2]. I use this estimate here by varying the radius in the simulation between these bounds.

## 2.2 Ablation and the Knudsen-Langmuir Equation

Ablation describes the process by which a meteoroid loses mass due to evaporation during its flight through an atmosphere. This effect is directly related to the kinetic energy transferred to the air molecules colliding with the meteorite. Ablation can have a substantial effect on the mass of a meteoroid if the atmosphere is sufficiently dense (which it is on Earth). Asteroids smaller than 25 m in diameter will almost completely burn up before reaching the surface of the Earth [3] and will likely impact as micrometeorites.

The rate of mass loss ($\frac{dm}{dt}$) can be calculated with the Knudsen-Langmuir equation [4] which I analyze here.

$$\frac{dm}{dt} = -4\pi r_o^2 P_{vap}(T_m)\sqrt{\frac{\mu}{2\pi k_B T_m}} \tag{1}$$

Equation (1) expresses the change in mass with respect to time using factors that take into account properties of both the atmosphere and the meteorite. The first, $r_o$, refers to the outer radius of the isothermal shell. The isothermal shell describes the depth to which the meteorite may be assumed to be isothermal (at a constant temperature, $T_m$). This shell exists because the surface of the meteorite is heated to the temperature of ablation almost instantly. It is therefore acceptable to always assume that the outer shell of the meteorite is at the temperature of ablation. The value of $r_o$ and hence the thickness of the isothermal shell is dependent on surface temperature which influences the rate of evaporation. I can calculate $r_i$ and consequently $r_o$ at each time step using an equation adapted from Love and Brownlee (1991) [5].

$$r_i = r_o - 0.3\frac{K}{\sigma T_s^3} \tag{2}$$

We see that the difference between $r_o$ and $r_i$ gives the thickness of the portion of the meteorite being heated. $r_o$ is initially just the radius of the meteorite (which changes when mass is lost due to ablation). The second term (which is being subtracted) represents the depth of isothermal penetration in the meteorite. $K$ is the thermal conductivity of the meteorite material and it has been calculated empirically for different materials by different authors. Here I take the average of the K values of iron and nickel (80 and 92 respectively [6]) to determine an approximate value for taenite. I therefore set K to 86. $T_s$ is the variable surface temperature of the meteorite and $\sigma$ is the Stephan-Boltzmann constant which I take from the IB Data Booklet.

$P_{vap}(T_m)$ represents the control of the mass loss by vapour pressure. Vapour pressure refers simply to the pressure exerted on the meteorite by the gaseous particles in the atmosphere. This quantity is more meaningful than melting and vaporization points in the rarefied upper atmosphere where the meteorite begins its flight path. This is why it is used here as a substitute. It can be calculated with the Clausius-Clapeyron equation [7].

$$log_{10}(P_{vap}(T_m)) = A - \frac{B}{T_m} \tag{3}$$

In equation (3) $A$ and $B$ are material dependent constants. These constants do not have any physical meaning by themselves. They were found by fitting a curve to empirical data. Substituting the values for an iron meteorite taken from Podolak et al [8] gives:

$$log_{10} P_{vap}(T_m) = 12.509 - \frac{20014}{T_m}$$

Returning to the analysis of equation (1), $T_m$ is simply the temperature of the meteorite, and $\mu$ and $k_B$ are both constants. They are the average mass of ablated particles and the Boltzmann constant respectively. The constant $k_B$ was taken from the IB data booklet, and $\mu$ is $1.4 \times 10^{-8}$ kg [4].

# 3 Methods

## 3.1 Creation of the Base Simulation

I designed the base simulation to crudely approximate the flight of a meteorite through an atmosphere. It assumed constant gravitational acceleration, it did not account for ablation, and it did not factor-in the large quantities of thermal energy going into heating the meteorite. It only described the vertical position of the meteorite ($z$) and its velocity in the same direction ($v$) accounting for atmospheric drag. I started by adding these components because I thought they were most important in representing the flight of the meteorite. I planned to build further complexity on top of this.

**Theorem 3.1**. To find the velocity of a meteorite as it falls towards the Earth through the atmosphere, I calculate the resultant force using formulas for the force gravitational acceleration ($F_g$) and drag ($F_d$).

$$F_d = \frac{C_d \rho v^2 A}{2} \ and \ F_g = mg$$

Where $C_d$ is the drag coefficient, $\rho$ is the density of the meteorite, $v$ is the velocity, and $A$ is the cross-sectional area. In the second equation $m$ is the mass of the meteorite, and $g$ is gravitational acceleration.

As these constants stay the same, I simplified the calculations by combining them into one constant $k$

$$k = \frac{C_d \rho A}{2}$$

We have

$$F_{net} = F_g - F_d$$
$$ma = mg - kv^2$$

Substituting $a = \frac{\Delta v}{\Delta t}$ we have

$$m(\frac{\Delta v}{\Delta t}) = mg - kv^2$$
$$\frac{\Delta v}{\Delta t} = g - \frac{kv^2}{m}$$

Thus the change in velocity,

$$\Delta v = (g - \frac{kv^2}{m})\Delta t$$

Substituting the original definition of $k$ and expressing velocity as the sum of the initial velocity $v_0$ and the change in velocity $\Delta v$ we have

$$v = v_0 + (g - \frac{C_d \rho A}{2m} v_0^2)\Delta t \tag{4}$$

**Theorem 3.2**. I can now derive the equation for the vertical position of the meteorite ($z$).

Assuming constant acceleration we can use the equation for position taken from the IB Data Booklet

$$\Delta z = v\Delta t + \frac{a\Delta t^2}{2}$$

Substituting $g - \frac{kv^2}{m}$ for $a$ gives

$$\Delta z = v\Delta t + (\frac{g - kv^2}{2m})\Delta t^2$$

Therefore I can express $z$ as

$$z = z_0 + v\Delta t + (\frac{g - C_d \rho A v^2}{4m})\Delta t^2 \tag{5}$$

Equations (4) and (5) were used to recalculate the velocity and the vertical displacement after an arbitrarily small time step epsilon until the meteorite made contact with the ground (i.e. its vertical displacement ($z$) is equal to zero). This is shown in Figure 1.

```
while z > 0:

    time += epsilon

    # update position
    z -= v*epsilon + 1/2 *(acceleration - k*v**2) * epsilon**2
    # update velocity
    v += (acceleration - k*v**2)*epsilon
```

Figure 1: Initial code for the main loop

## 3.2 Improving Calculations of Gravitational Acceleration

After the success of the base simulation I was ready to further complicate it. I improved the accuracy of the gravitational acceleration calculation from the base simulation using Newton's Law of Gravitation. Instead of using a constant, approximated parameter for this value, I calculate here it as a function of the meteorite's distance from the Earth.

$$g = \frac{GM}{r^2} \tag{6}$$

Newton's law of gravitation (equation (6)) calculates the gravitational acceleration ($g$) using radius ($r$), a constant parameter, and the mass of the attracting body.

Let the acceleration due to gravity at distance $x$ be $g(x)$. I know the mass of the earth ($M$) is $5.972 \times 10^{24}$ kg and that the radius of the Earth is $6.371 \times 10^6$ meters. The distance from the meteorite to the center of the Earth is the sum of the radius of the Earth and the meteorite's distance from its surface:

$$r = 6371000 + x$$

Substituting $r$ in equation (6) I have

$$g(x) = \frac{G(5.972 * 10^{24}}{(6371000 + x)^2} \tag{7}$$

Equation (7) was coded as a function which is shown in Figure 2.

```python
def calc_g(position: int):
    """g = GM/r^2"""
    # mass of the earth
    m_planet = 5.972 * 10**24
    # radius of the earth plus the distance
    r = (6371 * 1000) + position

    return 6.67 * 10**-11 * m_planet / r**2
```

Figure 2: Function for calculating acceleration due to gravity

### 3.3 Calculating Mass Loss due to Ablation

The mass of the meteorite was also recalculated at each time step to reflect the mass lost due to ablation as a result of the intense thermal exchanges between the meteorite and the atmosphere. This was done using the Knudsen-Langmuir equation (equation (1)).

```python
def calc_mass(temp: int, t: int):
    """Using the Knudsen-Langmuir equation to calculate mass loss due to ablation"""
    p_vap = 10**(12.509-20014/temp)
    c = math.sqrt(1.4*10**-8/2*math.pi*1.38 * 10**-23 * temp) * t

    return -4 * math.pi * 0.001**2*p_vap * c
```

Figure 3: Function to calculate mass loss due to ablation

The code shown in Figure 3 shows a functional implementation of equation (1). $P_{vap}(T_m)$ and the square root value are calculated separately and combined to give the result. I multiply the product by $\Delta t$ to be left with $\Delta m$ which is what the function returns.

**Theorem 3.3**. I derived an equation for the temperature of the meteorite ($T_m$) that I use in the (*calc_mass*) function shown in Figure 3 based on energy transformations. I assume that all energy lost due to friction goes towards heating the meteorite. The implications of this assumption are discussed more in Section 7.
We have

$$\Delta E = F_d \Delta z$$

Substituting $\Delta E$ with the equation for heat transfer gives

$$mc\Delta T = F_d \Delta z$$

Replacing $c$ with the specific heat capacity of iron (450 J/ kg) and isolating $\Delta T$ gives

$$\Delta T = \frac{F_d \Delta z}{450m}$$

Which I can rewrite as

$$T_m = T_0 + \frac{F_d \Delta z}{450m} \tag{8}$$

$T_m$ is incremented until it reaches the boiling point of taenite (2863 deg C) [9] at which point all further energy is assumed to go into ablating the meteorite (this is a simplification which I discuss more in Section 7). This increment is performed at each time step as shown in Figure 4.

```python
if (temp < 2863):
    temp += DRAG * DENSITY * area/2 * delta_z* v**2/(450*mass)

mass += calc_mass(temp, time, radius)
```

Figure 4: Condition to decrease the mass by the quantity ablated

# 4 Results

I varied the radius of the meteorite from 5000 to 8000 meters in increments of 750 meters and calculated the meteorite's kinetic energy at the moment of impact for each value. For each value of the radius, I ran three trials each with a unique value for epsilon (the time step): 0.05, 0.01, and 0.015. 0.01 is 50% greater and 50% less than the other two values respectively. By understanding the proportional change in the measured variables for a percentage change in epsilon, I can better understand the uncertainty in our results. This is discussed more in Section 5.

## 4.1 General Results

| Initial Radius (m) | KE at Impact (kJ) | Final Mass (kg) | Final Radius (m) | Final Velocity ($ms^{-1}$) |
|---:|---:|---:|---:|---:|
| 5000 | $2.29{\times}10^{15}$ | $5.24{\times}10^{11}$ | 4940 | 2950 |
| 5750 | $3.49{\times}10^{15}$ | $7.96{\times}10^{11}$ | 5690 | 2950 |
| 6500 | $5.04{\times}10^{15}$ | $1.15{\times}10^{12}$ | 6440 | 2950 |
| 7250 | $6.99{\times}10^{15}$ | $1.60{\times}10^{12}$ | 7190 | 2950 |
| 8000 | $9.39{\times}10^{15}$ | $2.14{\times}10^{12}$ | 7940 | 2950 |

Table 1: Data for epsilon = 0.01

Table 1 shows the data I collected when epsilon was set equal to 0.01. Here I round the values to three significant figures somewhat arbitrarily to make the data easier to read. Actually, all of the digits I collected are significant because there is no random error in the simulation. This increased accuracy will be apparent when I process the resulting data. The complete dataset can be found in Appendix 1 along with the data for the other two values of epsilon. They are not shown here for sake of brevity as I would be required to express the data with greater precision to illustrate subtle differences.

## 4.2 Results for Individual Quantities

Using a simulation affords one the luxury of being able to measure any recorded property of the simulation at each time-step with complete accuracy. I will show here how the measured quantities (velocity, radius, mass, and KE) evolved over the duration of each simulation. Since we are looking only at the relationships between each of these variables and time, the actual values I plot are irrelevant. For this reason, I did not plot the data for each time step or for each radius because doing so would only produce the same relationship. For Figures 5 - 8, I used a time step of 0.01 and an initial radius of 8000 meters.

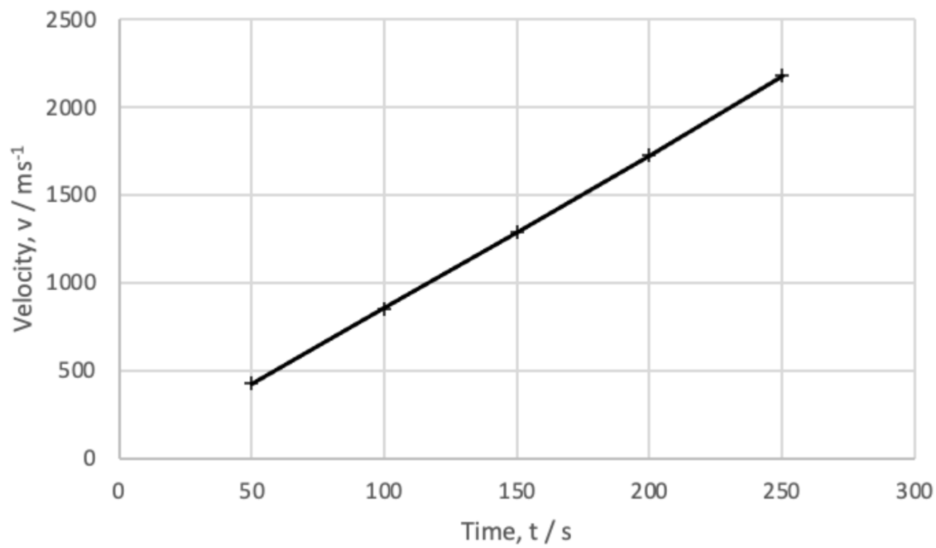


Figure 5: Velocity plotted against time

Figure 5 shows that velocity varies roughly linearly with time which confirms an expected relationship. I know that acceleration will only increase slightly as the simulation progresses so it should appear roughly constant on a graph like the one in Figure 5. Since the function shown is roughly linear and because acceleration is its derivative, I can confirm that this result is accurate. The slight variation in slope is due to slightly changing gravitational acceleration.

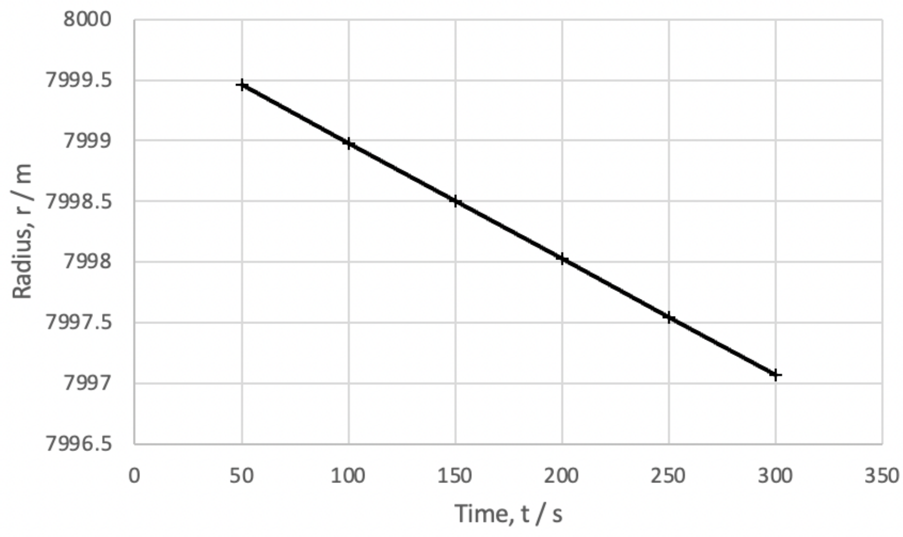


Figure 6: Radius plotted against time

Figure 6 plots the outer radius of the meteorite as the experiment progresses. The function is completely linear meaning that it is losing radius at a constant rate which is described by equation (2). This loss in radius begins after the meteorite reaches the boiling point of taenite.

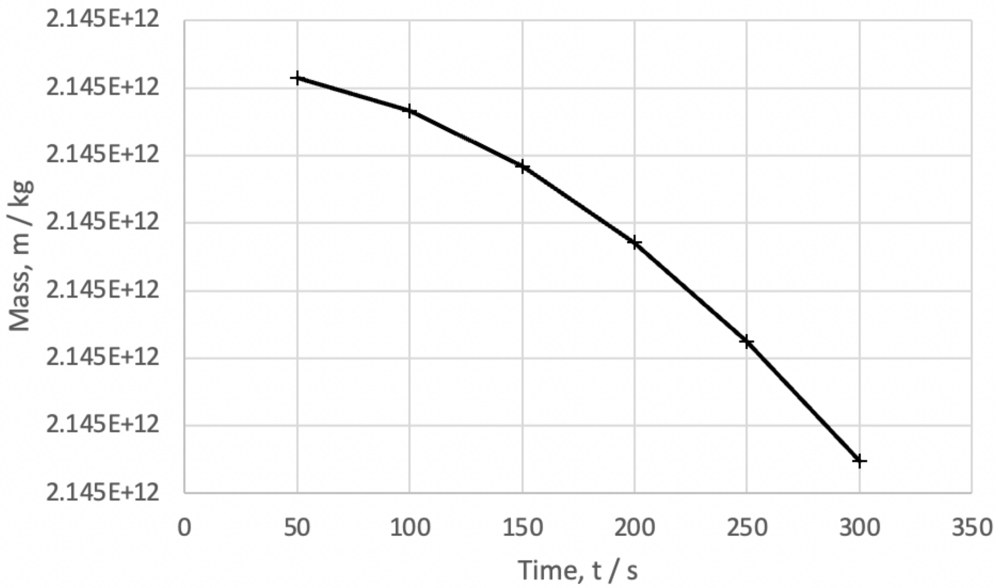


Figure 7: Mass plotted against time

Figure 7 shows that mass decays at an increasing rate as the experiment progresses. Since the density of the meteorite remains constant, I can attribute this variation to the linearly decreasing outer radius of the meteorite as it is ablated (shown in Figure 6). Since the volume of a sphere is dependent on the cube of the radius so too is the mass of the meteorite which is just a product of this volume and a constant density. I can therefore classify this curve as a polynomial of degree three.

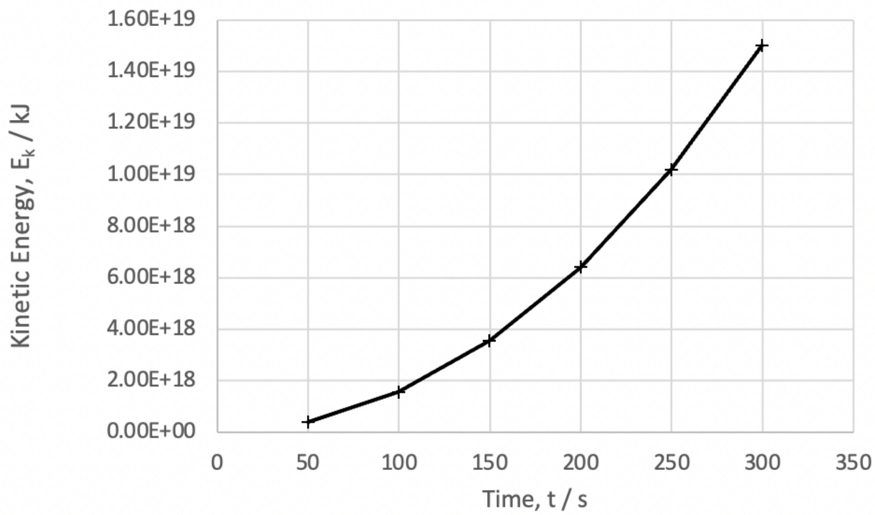


Figure 8: Kinetic energy plotted against time

Putting these quantities together allows us to look at how they affect the kinetic energy (KE) of the meteorite. In Figure 8, I see that the KE grew at an increasing rate as the simulation progressed. KE is linearly dependent on mass and dependent on the square of velocity so this result makes sense. I know from Figures 5 and 7 that velocity is varying linearly with time and that mass decay can be described by a cubic function. Therefore, the function describing KE is also a polynomial of degree three.

## 4.3 Measured Values of Kinetic Energy, Radius, and Mass at Impact

Plotting the values for KE shown in Table 1 gives the graph shown in Figure 9.

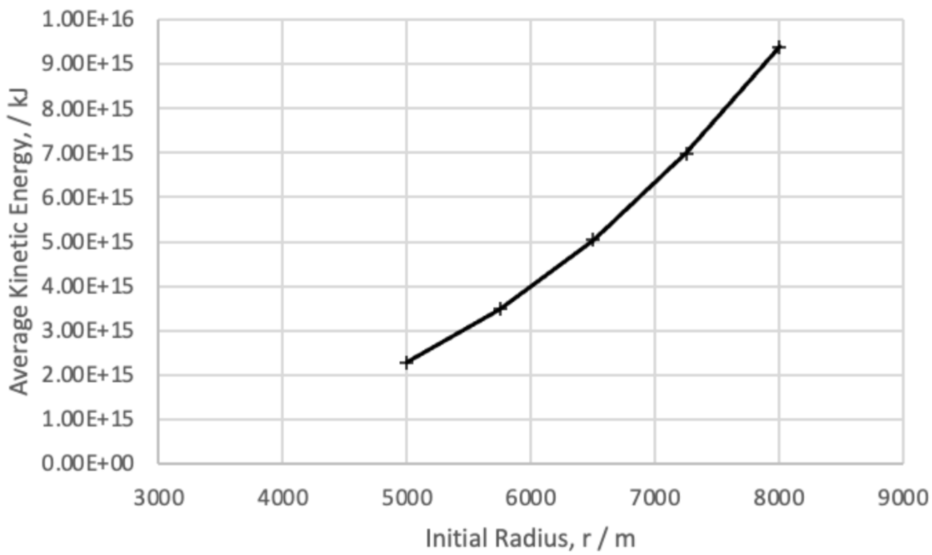


Figure 9: Final kinetic energy plotted against the initial radius of the meteorite

The data was fit perfectly with a cubic function. We can examine the reason for this relationship by examining the components of kinetic energy.

$$E_k = \frac{mv^2}{2} \tag{9}$$

In equation (9) we see KE is proportional to the square of the radius and directly proportional to the mass. Velocity does not depend on radius so the meteorite's final velocity is constant across all of the data. The mass though is proportional to the cube of the radius. Since KE is proportional to mass, KE is also proportional to the cube of the radius. This gives the curve shown here.

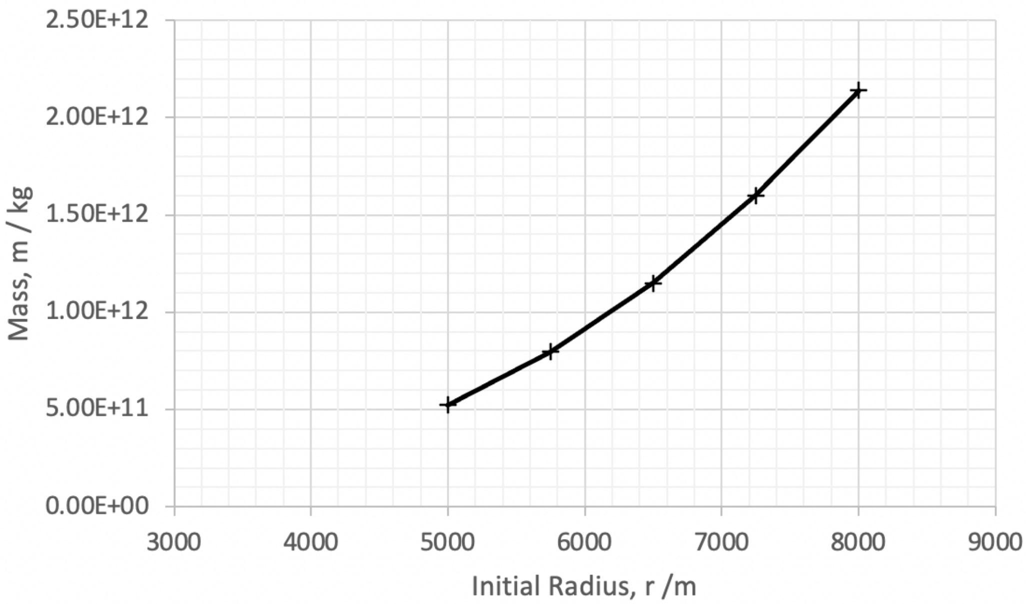


Figure 10: Final mass plotted against the initial radius of the meteorite

Looking at the final mass (Figure 10) I see that I can fit the data perfectly with a quadratic function. By equation (1) I know that the only variable factor impacting the change in mass is $T_m$. Since the surface area of the meteorite (the area being heated) is proportional to the square of the radius this relationship is logical.

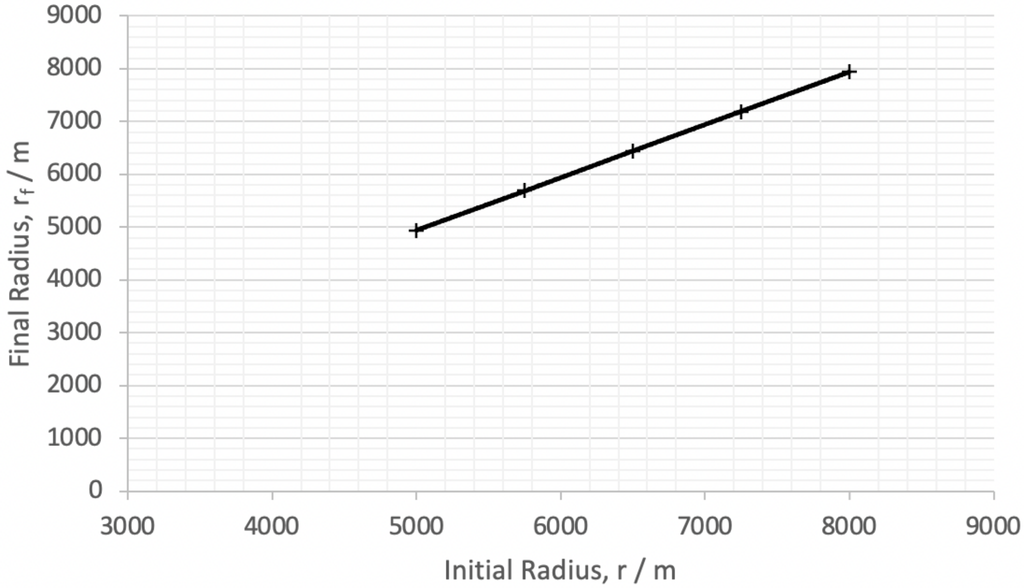


Figure 11: Final radius plotted against initial radius

Figure 11 shows a perfectly linear correlation between final and initial radius. This is because the radius of the isothermal shell does not depend on the initial radius of the meteorite. Since the rate of ablation depends on the radius of the isothermal shell and this value does not change among different radii, it must be constant.

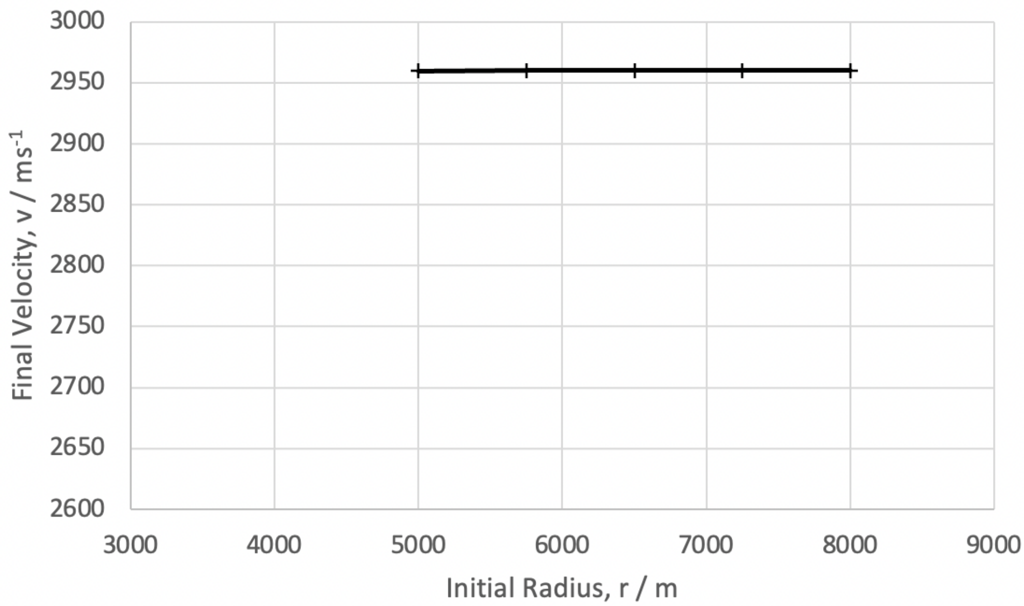


Figure 12: Final velocity plotted against initial radius

Finally I show that the final velocity of the meteorite is roughly constant. As the meteorite increases in size, the drag force acting on it increases by an amount proportional to the change in cross-sectional area which is the reason for the slight variation.

# 5 Error Analysis

We see from Figure 9 that the greatest KE attained was $9.39\times10^{15}$ kJ and the smallest was $2.29\times10^{15}$ kJ when the radius was at the bottom of the possible range. The difference in these values is $7.1\times10^{15}$ kJ. I can therefore state that KE $= (5.84 \pm 3.55) \times 10^{15}$ kJ.

We can better understand the precision of the simulation by looking at how the measured values change for a corresponding change in the time step. As the time step approaches 0, I should expect these results to be more accurate. I performed a resolution test to quantify this precision.

| Initial Radius (m) | Average KE Resolution (%) |
|---:|---:|
| 5000 | 0.0066 |
| 5750 | 0.0063 |
| 6500 | 0.0062 |
| 7250 | 0.0059 |
| 8000 | 0.0058 |

Table 2: Average data for the KE resolution test

The values in the second column of Table 2 are the average percentage changes in KE when I change the time step by 50% in either direction. I see that the change in all cases was less than 1/100 of a percent. This tells use that the time steps I used produced extremely precise results. We compute the difference in resolution for time steps of 0.05 ($KE_1$) and 0.15 ($KE_3$) compared to 0.1 ($KE_2$). Sample calculation for an initial radius of 5000 m:

$$\begin{aligned}\frac{KE_1}{KE_2} &= \frac{2293575905441770}{2293638333776830} \\ &= 0.999972781962116\end{aligned}$$

$$\begin{aligned}\frac{KE_3}{KE_2} &= \frac{2293877744243010}{2293638333776830} \\ &= 1.00010438021664\end{aligned}$$

Computing the average percent change we have

$$\begin{aligned}res &= ((1 - \frac{KE_1}{KE_2}) + (\frac{KE_3}{KE_2} - 1))/2 \times 100 \\ &= 0.0066\%\end{aligned}$$

# 6 Conclusion

In conclusion, I successfully created a simulation that measured the kinetic energy at impact of a meteorite. I tested it with values corresponding to the meteorite that created the Sudbury basin. I showed that KE ranges from $2.29\times10^{15}$ to $9.39\times10^{15}$ kJ. This large difference between the lower and upper bounds is due to large variation in the predicted values for the radius of the meteorite. Our results are based on a model that made a number of assumptions which I discuss in more depth in Section 7. Notwithstanding, I can safely assume that the actual value for the kinetic energy of the meteorite was on the same order of magnitude as my results. I can therefore make accurate general conclusions about how this may have impacted the formation of the basin. Furthermore, my model predicted an extremely small amount of ablation. Each value for the outer radius at impact was only about 57 meters less than its original value. Even if the actual Sudbury meteorite was on the extreme lower half of the range, by the time it hit the ground it would still be over 9885 meters in diameter.

The massive amount of energy associated with this impact would have launched debris much further away than what is now the Sudbury area. The basin itself though would still contain the bulk of the materials present in the meteorite. The meteorite would have been able to travel a considerable distance into the Earth's crust which explains the current need to mine the materials from far below the surface. The energy of the meteorite also explains the crater's size which is roughly 360 times larger than lethal area of the atomic bombs used in WW2.

I also calculated lower and upper bounds for the final mass ($5.24\times10^{11}$ $2.14 \times 10^{12}$ kJ), the final radius (4942 to 7943 m), and the velocity of the meteorite at impact (2959 $ms^{-1}$). I estimate that the meteorite spent 332.3 seconds in the Earth's atmosphere before colliding with the surface and creating the basin.

I showed that there is an extremely small error in the simulation by testing the resolution of KE for different time steps. The greatest percentage error was 0.0066% (Table 2).

## 7 Evaluation

It is important to restate that these results are based on data collected from a model that makes a number of simplifying assumptions. The largest assumption I make is that the meteorite assumes a perfectly spherical geometry. Despite this ostensibly being a large simplification, the effect it has on the data is likely relatively small. Assuming a spherical shape is synonymous with assuming a constant radius which only has a large impact on the uniformity of surface ablation and the cross sectional area of the meteorite. A more realistic, less spherical meteorite might have a slightly larger cross sectional area, and might ablate less predictably. The cross sectional area is proportional to the force of drag on the meteorite so increasing it would result in a proportional decrease in the final velocity of the meteorite. It is likely that the difference is small, but even a small difference could create significant variation in KE because it is proportional to the square of velocity. The effect of abnormal ablation is much smaller. Irregular ablation might result in a final mass that is slightly greater or less than what I predict, but it would not drastically impact final KE.

I also assume that the meteorite has uniform density. I know that, in reality, the Sudbury meteorite likely contained materials of different densities like cobalt or silicon. An irregular density would impact both the force of drag and the mass of the meteorite. If the meteorite had a greater portion of its mass centered on one section it may have also fallen with an irregular orientation. Notwithstanding, I can still be confident about the nature of my results. Even if the mass was much different than what I calculated, my results would inhabit a set of values that would allow us to draw similar conclusions.

The last large assumption I made was that all the meteorite's kinetic energy lost to friction went into heating the meteorite. In reality, part of the lost energy would create sound or heat the surrounding air. It is very hard to accurately calculate the distribution of lost energy making this simplification necessary. The result is that I predicted the meteorite increased in temperature faster than it would have.

# 8 Future Work

Computer models can always be made to reflect the real-world more accurately. In future studies I plan to address many of the shortcomings in our model discussed in Section 7. The first of which is the assumption that the meteorite was made solely of taenite. I propose a more extensive literature review of work pertaining to the Sudbury basin to better approximate the proportion of materials in the meteorite. This would result in a more accurate estimation of its density which would likely be greater than the one I propose.

I could also estimate the cross sectional area of the meteorite without actually encoding an irregularly shaped meteorite into the simulation. This would improve the calculation of drag and would thus result in a more accurate final velocity. This value could likely be estimated based on others in the literature.

Lastly, I could attempt to predict the proportion of heat energy that actually goes into heating the meteorite. To do this, I may look at past studies that have empirically measured the temperature of a meteorite after it has made contact with the Earth. Given some properties of the meteorite, I could first estimate the energy lost due to friction with our model. I could then calculate $\Delta E$ with the empirical value for temperature and then compare these two. This would give us an idea of the fraction of lost energy that goes into heating the meteorite.

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# A Appendix 1

| Radius (m) | Kinetic Energy (kJ) | Mass (kg) | Final Radius (m) | Final Velocity (m/s) |
|---|---|---|---|---|
| 5000 | 2293638333776830 | 523581920361.834 | 4942.759688 | 2959.955257 |
| 5750 | 3488349745517690 | 796305388227.739 | 5693.12337 | 2959.955495 |
| 6500 | 5039160142002860 | 1150317579887.32 | 6443.007437 | 2959.955619 |
| 7250 | 6992511154508640 | 1596219985970.54 | 7193.137733 | 2959.955689 |
| 8000 | 9394854073945030 | 2144616302776.92 | 7943.212187 | 2959.95573 |

Table 3: Data for epsilon = 0.01 shown with all significant figures

| Radius (m) | Kinetic Energy (kJ) | Mass (kg) | Final Radius (m) | Final Velocity (m/s) |
|---|---|---|---|---|
| 5000 | 2293575905441770 | 523565265142.6 | 4937.02737621671 | 2959.96205300788 |
| 5750 | 3488271532551520 | 796283877605.985 | 5687.09343981365 | 2959.96229146353 |
| 6500 | 5039057858906490 | 1150288949252.56 | 6437.34233680702 | 2959.96241520395 |
| 7250 | 6992393112445740 | 1596185710583.71 | 7187.18363553715 | 2959.96248455169 |
| 8000 | 9394713940802350 | 2144574466564.33 | 7937.23219971039 | 2959.96252582527 |

Table 4: Data for epsilon = 0.005 shown with all significant figures

| Radius (m) | Kinetic Energy (kJ) | Mass (kg) | Final Radius (m) | Final Velocity (m/s) |
|---|---|---|---|---|
| 5000 | 2293877744243010 | 523586896679.618 | 4940.67049207775 | 2960.09566603832 |
| 5750 | 3488713903326090 | 796312966512.098 | 5690.47287480075 | 2960.09590482961 |
| 6500 | 5039682220558110 | 1150327620597.69 | 6440.07311967996 | 2960.0960287354 |
| 7250 | 6993224721908460 | 1596231433945.42 | 7190.69434049062 | 2960.09609811657 |
| 8000 | 9395809646188470 | 2144630965307 | 7940.5037275959 | 2960.09613943135 |

Table 5: Data for epsilon = 0.15 shown with all significant figures