European Association for Astronomy Education

Catch a Star 2015

Title:

¡Great impacts!

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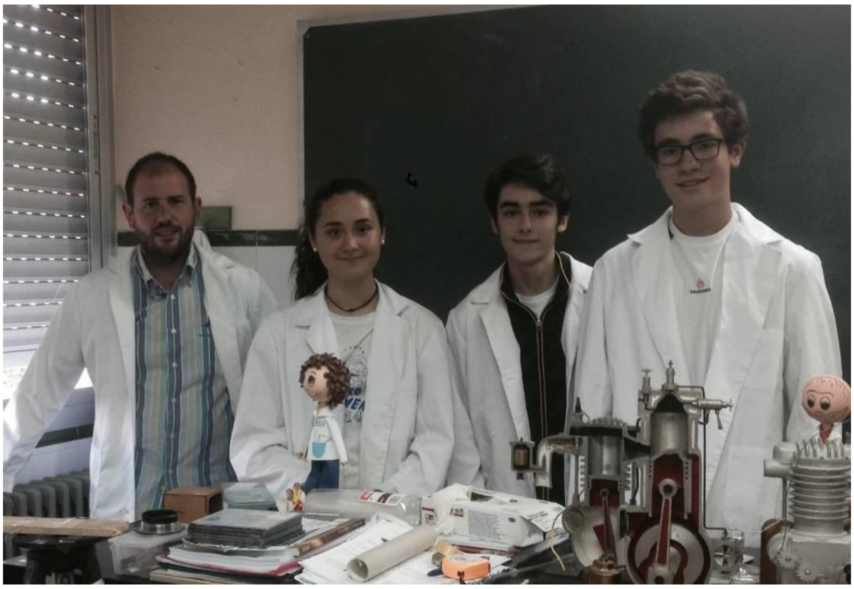

Abstract

Four years ago our older colleagues of School showed in *Ciencia en Acción* (Lleida, Spain) and in EAAE (European Association for Astronomy Education) a paper entitled "*The sizes in the Moon*." Here diameters and depths of the biggest craters of our natural satellite were calculated. We used to wonder how they would have formed. And the answer was clear: powerful meteorite impacts that occurred long time ago. But what are their exact parameters?

In this current study we intend to show a fairly logical and rigorous procedure about how such impacts occurred.

The first clue to start our study was the analysis of the limited data that we found about the event on Earth known as *Barringer Crater* (or *Meteor Crater* in Arizona). The conclusions drawn in this study were extrapolated to the case of what could happen in the Moon (taking into account the logical differences between the two contexts).

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Development

Introduction

45,000 years ago a nickel-iron meteorite, between 40 and 50 meters (160 feet) in diameter and a mass of about 300 million kg, had an impact on the west of the United States (in Arizona) with a speed of about 12 km/s. The collision had to release - at least - an energy equivalent to the explosion of 2.5 megatons (2.5 million tons of TNT).

Figure 1. Meteorite approximation and imminent impact
(Artistic image homemade)

The result of that past event can still be seen in what is now known as *Meteor Crater* or *Barringer Crater*. The *Barringer crater* has a diameter of 1200 m, its edges rise above the level ground 45 m and has today a depth of 170 m. Some expelled fragments of limestone have been found in an area of 260 Km^2.

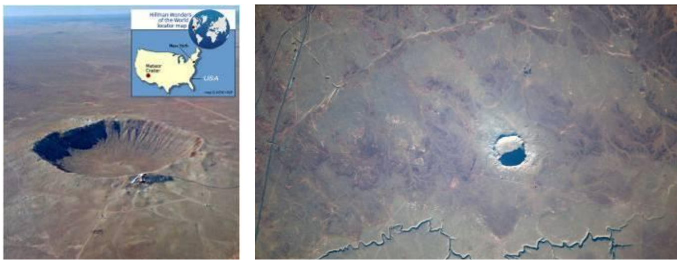


Figure 2 & 3. Barringer crater

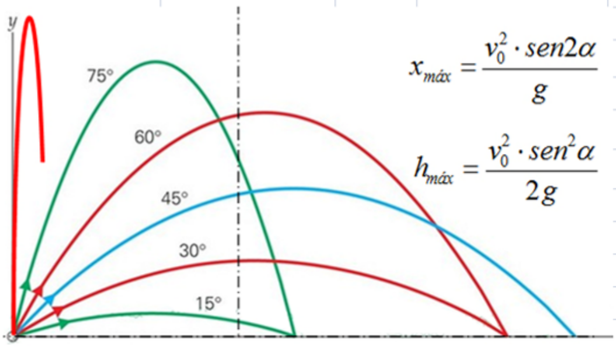
And this is all the information we have found about this famous crater.

It was then that we wondered how such as precise details on this brutal collision could be known.

Preliminary investigations: Observations on the site

The first clue that we found were the fragments which were found in the area. The remains, which extend in a circular area, would reach a distance that can be calculated:

$$260Km^2 = \pi \cdot R^2 \quad \Rightarrow \quad R = \sqrt{\frac{260}{\pi}} = 9{,}097Km = 9097m$$



$$x_{máx} = \frac{v_0^2 \cdot sen2\alpha}{g}$$

$$h_{máx} = \frac{v_0^2 \cdot sen^2\alpha}{2g}$$

Restos 260 Km^2	
9,097	Radio (Km)
298,7	v_0 según alcance máximo (m/s)
4548,6	Altura$_{máx}$ (m)

Figure 4. Scope and heights in oblique shots

The maximum range at an oblique release is related to the initial velocity output by the expression:

$$x_{máx} = \frac{v_0^2 \cdot sen2\alpha}{g}$$

And as we know that scope, we can calculate the initial velocity of the fastest fragments:

$$9097 = \frac{v_0^2 \cdot sen90}{9{,}81} \quad \Rightarrow \quad v_0 = 298{,}7 \, m/s$$

Once known the initial rate, we can also calculate the maximum height reached by some of them:

$$h_{máx} = \frac{v_0^2 \cdot sen^2\alpha}{2g} \qquad h_{máx} = \frac{v_0^2 \cdot sen^2 90}{2 \cdot 9{,}81} = 4548{,}6m$$

Actually, the output speed should be higher because the air friction must greatly curb the scope of all the fragments expelled. However, we will keep these values to begin our analysis.

The second clue is found in own Barringer Crater.

Based on the size of the crater, we dared to make an estimate of the volume of rock ejected on impact (and the mass of this volume).

But we must first analyze how an impact crater is formed and how it evolves over time.

After a strong impact, the enormous pressure generated in the subsurface produces some elevation of the surrounding terrain.

Over the years, part of the primary edge collapses and go back causing a bit wider crater than originally.

On the other hand, much of the material would fall in the same place and would fill a part of the original hole.

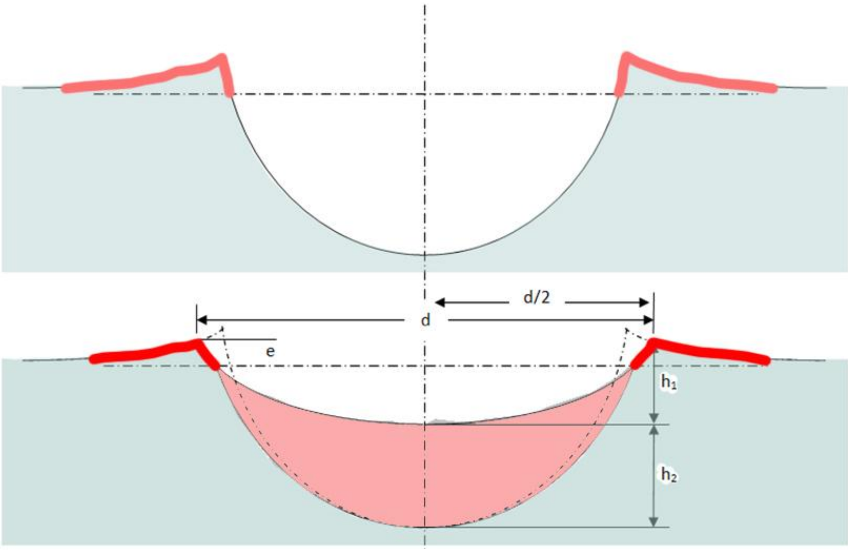


Figure 5. Geometry parameters of an impact crater
(Homemade)

We learned that in the Barringer crater had done prospections to 240 m depth, where it was - finally - the bedrock floor.

All this leads to believe that the meteorite of Arizona emptied a hollow - in the form of a spherical cap - of 1110 m in diameter and a total depth of 365 m.

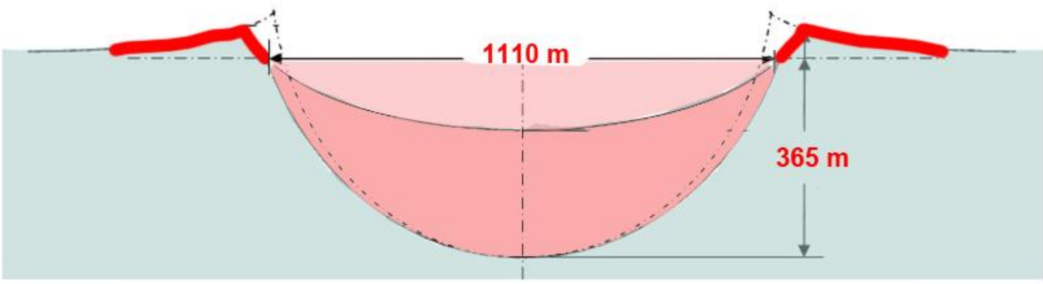
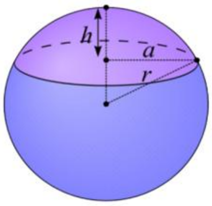


Figure 6. Estimated volume of rock ejected



We can calculate the volume of material ejected by the expression:

$$V = \frac{\pi \cdot h}{6}(3a^2 + h^2) = 202.064.359{,}5 m^3$$

The density of the limestone is 2500 kg/m^3 – the soil composition of the area - so we can also know the mass ejected:

$$d = \frac{m}{V} \quad \Rightarrow \quad m = d \cdot V = 5{,}05161 \cdot 10^{11} Kg$$

However, not all this amount of material would reach the maximum values of energy we have seen above.

A reasonable statistical approach leads us to believe that not more than one a quarter (25%) did.

In this way (by considering $h = \frac{h_{máx}}{4}$), we could estimate the impact energy in:

$$E = mgh = 5{,}486 \cdot 10^{15} J$$

And if we assume that another part equivalent was invested to produce heat, we would have a total:

$$E_{total} = 1{,}097 \cdot 10^{16} J$$

This is a double value of the previous which is consistent with the 2.5 Mtons that we have read in our sources of information.

Looking for a culprit

We could assume that the speed of the impact was 12 km/s. It is a fairly reasonable option because the escape velocity from our Earth is 11.2 km/s. It is as if an object falling from infinity attracted by our gravity. Of course that could happen with higher values, but this basic assumption is a good choice to start.

Moreover, we have found many fragments of molten iron and nickel across the impact area, which suggest that the meteorite had a typical composition and density of 7000 Kg/m^3.

Figure 7. Meteorite fragment found in the crater Barringer

From the energy and speed of the impact that we calculate above, we deduce the mass that the meteorite might have:

$$E = \frac{1}{2} m v^2 \quad \Rightarrow \quad m = \frac{2E}{v^2} = 152.000.000 Kg$$

However, entering into the atmosphere, half of the total mass had to disintegrate, so the original mass of the meteorite should be twice:

$$m_{total} = 304.000.000 Kg$$

And this value is also consistent with the initial data that we found.

From the density of nickel iron material we can now estimate the volume:

$$d = \frac{m}{V} \quad \Rightarrow \quad V = \frac{m}{d} = 43396{,}8 m^3$$

Assuming that the meteorite had spherical shape, we can determine the radius:

$$V = \frac{4}{3} \pi \cdot R^3 \quad \Rightarrow \quad R = 21{,}8 m \quad \Rightarrow \quad Diámetro \cong 44 m$$

The last calculation is also consistent with the information we had found about.

Extrapolating ideas and calculations

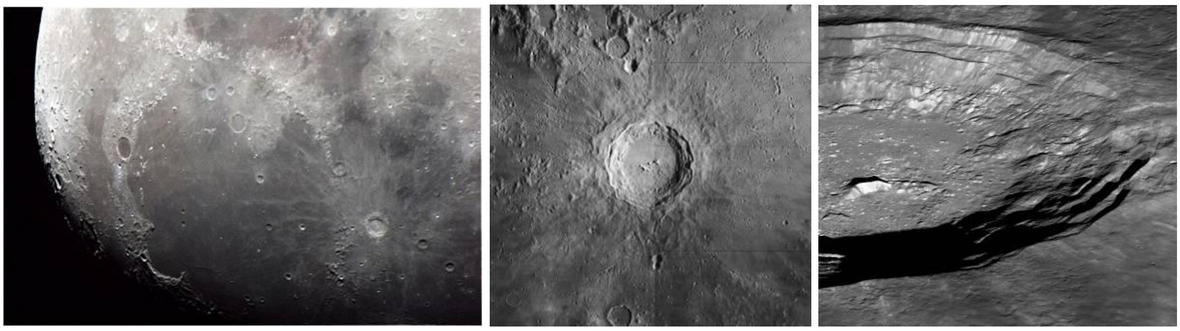
We believe that such events often have a typical behavior that is repeated in many impacts and thus, we dared to extrapolate our calculations.

Figure 8, 9 & 10. Similarities found in various impact craters

We started doing a similar study in the lunar crater named *Copernicus*.

Copernicus has a diameter of 93 kilometers (it´s huge!) and a depth of 3800 m (the highest mountains in our area would fit inside!).

The ridges that form the crater rim towering over the plain *lunar maria* level to a height of 1006 m.



Figures 11, 12 & 13. Notable aspects observable in the crater *Copernicus*

First, we analyze the materials ejected. We can estimate that they reaches 651 km away (about 7 times the diameter of Copernicus within a gravity that is 1/6 that of Earth)

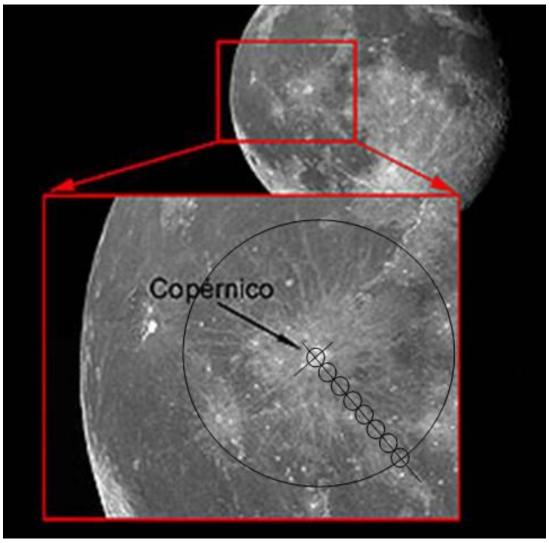
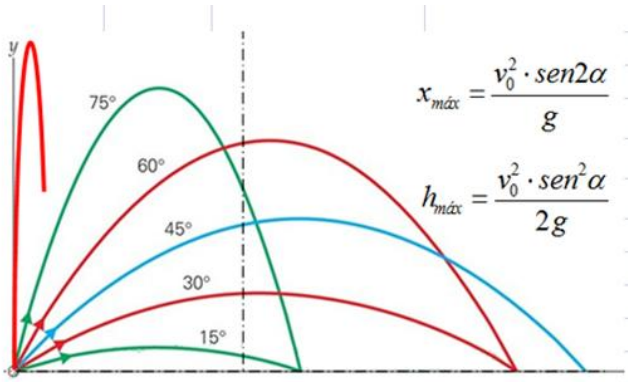


Figure 14. Estimate the scope of the ejecta



$$x_{máx} = \frac{v_0^2 \cdot sen2\alpha}{g}$$

$$h_{máx} = \frac{v_0^2 \cdot sen^2\alpha}{2g}$$

Eyecciones	
93	Diámetro (Km)
651	Radio, $x_{máx}$ (Km)
1032	v_0 según alcance máximo (m/s)
325500	$Altura_{máx}$ (m)

Figure 15. Scope and heights in oblique shots at the moon

As before, we estimate the initial maximum speed of expulsion of materials through the maximum length observed:

$$x_{máx} = \frac{v_0^2 \cdot sen2\alpha}{g} \qquad 651000 = \frac{v_0^2 \cdot sen90}{1,635} \quad \Rightarrow \quad v_0 = 1.032 \, {}^{m}\!/_{s}$$

And also the maximum height reached by some of them:

$$h_{máx} = \frac{v_0^2 \cdot sen^2\alpha}{2g} \qquad h_{máx} = \frac{v_0^2 \cdot sen^2 90}{2 \cdot 1{,}635} = 325.500m$$

This time, without air friction, we can rely more on the results.

If, as we mentioned before, the Barringer Crater behavior is extensible to other similar formations, we can also estimate that inside Copernicus Crater there may be debris to a depth of 5365 m.

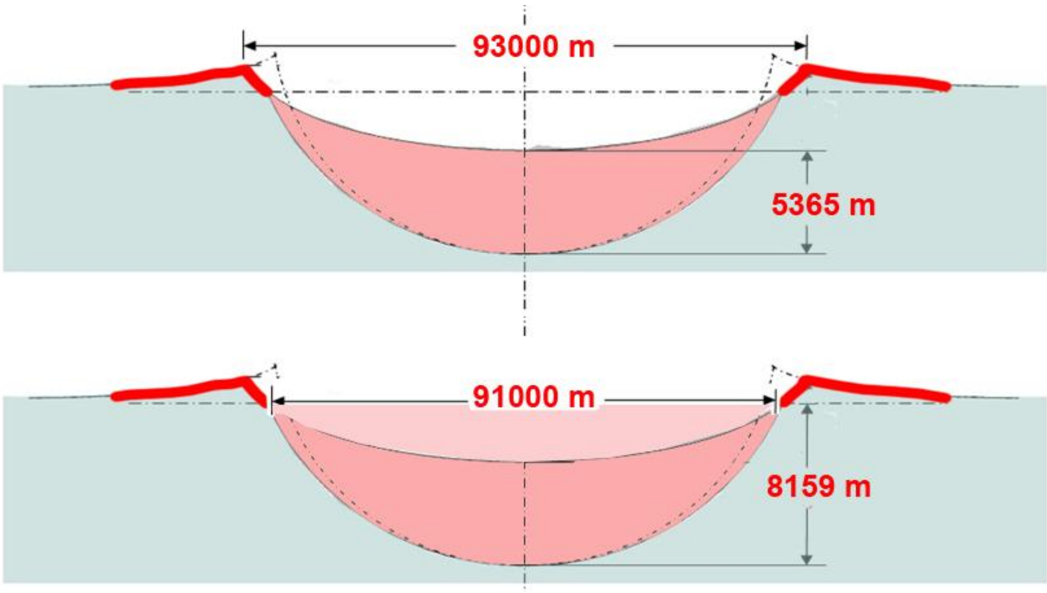
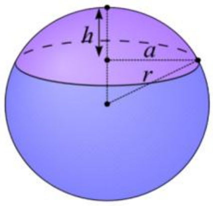


Figure 16. Geometry parameters of the crater Copernicus and estimate the volume of ejected material

Then we can calculate the volume of material ejected with the known expression:



$$V = \frac{\pi \cdot h}{6}(3a^2 + h^2) = 2{,}618 \cdot 10^{13} m^3$$

The average density of *pyroxene* (predominant material on the *lunar maria*) is 3000 kg/m^3, so from this density, we know the mass ejected:

$$d = \frac{m}{V} \quad \Rightarrow \quad m = d \cdot V = 8{,}043 \cdot 10^{16} Kg$$

If a quarter of the total mass got the maximum height, we would have an impact-energy:

$$E = mgh = 1{,}070 \cdot 10^{22} J$$

Twice in fact, if we consider another amount equal transformed into heat:

$E_{total} = 2{,}140 \cdot 10^{22} J$ (Equivalent to: 5,515 billion Tons of trinitrotoluene!)

And now let´s go hunting the responsible!

This time, we assume an impact speed of 5 km/s. It's also a reasonable option because the escape velocity on the moon is 2.38 km / s. We increase this value due the closeness of our Earth.

From the calculated energy at this moment and the impact velocity, we deduce the mass of meteorite that fell on the area:

$$E = \frac{1}{2} m v^2 \quad \Rightarrow \quad m = \frac{2E}{v^2} = 1{,}712 \cdot 10^{15}\, Kg$$

This time we will retain this value - without additional corrections - because there isn't any loss of mass caused by friction with the atmosphere.

Then we can calculate the volume of the meteorite ($d = \frac{m}{V} \quad \Rightarrow \quad V = \frac{m}{d}$)

But at this point we do have to analyze what would be its composition.

We considered four possible types:

Material	***Nickel-iron***	***Ferrous-metal***	***Chrondritic***	***Cometary material***
Density	7000 Kg/m^3	4250 Kg/m^3	3250 Kg/m^3	600 Kg/m^3

Assuming that the meteorite had spherical shape ($V = \frac{4}{3}\pi \cdot R^3$), we can then estimate its size. We show radius and diameters found:

Material	***Nickel-iron***	***Ferrous-metal***	***Chrindritic***	***Cometary material***
Density	7000 Kg/m^3	4250 Kg/m^3	3250 Kg/m^3	600 Kg/m^3
Radius	3879 m	4581 m	5031 m	8798 m
Diameter	**7758 m**	**9162 m**	**10062 m**	**17596 m**

We will not make written comments on these results. But instead, we represent to scale how would the body that fell on the Moon and the size of the impact here on Earth in our environment.

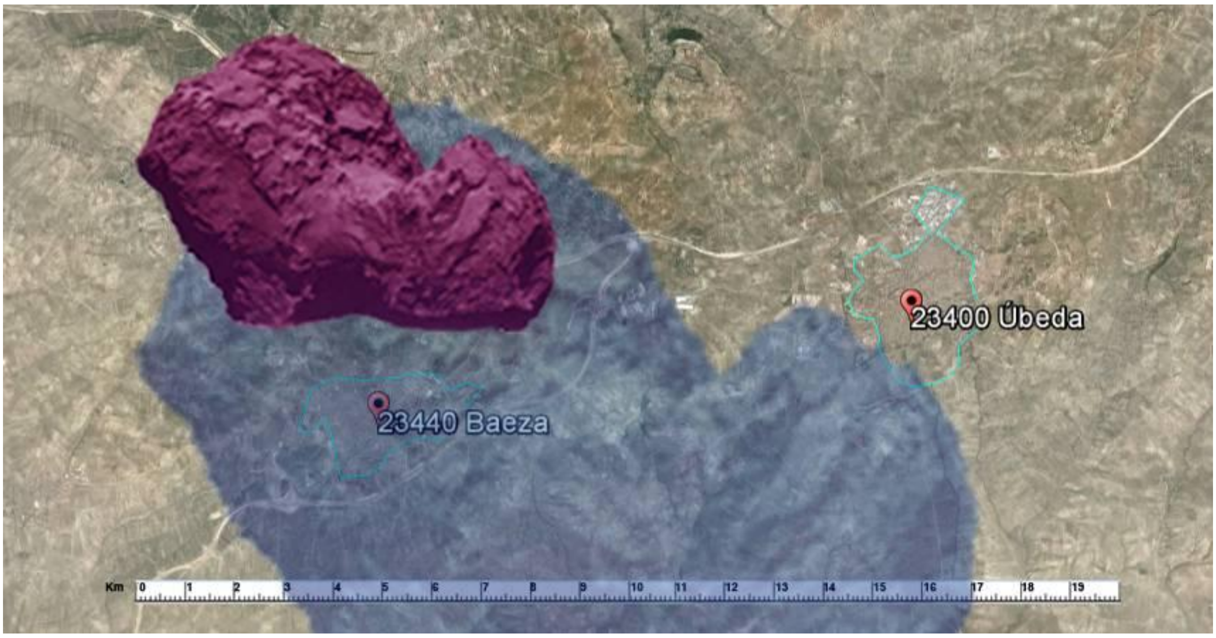


Figure 17. Representation two sizes meteorite that caused the crater Copernicus
(7758 m for Fe-Ni y 17596 m for cometary material)

Figure 18. Copernicus size comparison with our environment

Figure 19. Simulation of what would be Copernicus in our environment

Figure 20. Representation of the reach of ejecta

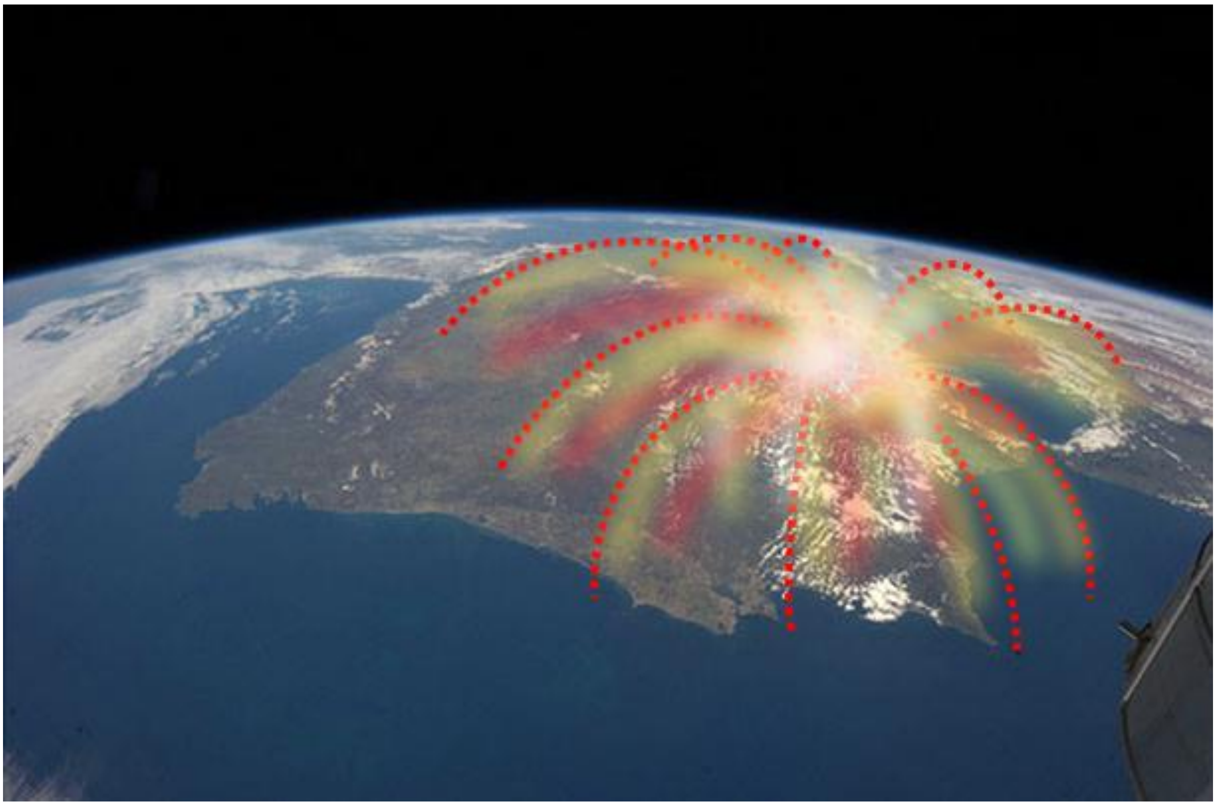


Figure 21. Simulation heights reached by the ejecta

Conclusion

There is no intention here to do a rigorous study of what could happen in any of the cases analyzed. But it is a work of multidisciplinary research that brings into play knowledge and skills in all our students.

Still, the values we have found largely coincide with those found quite reliable sources of information and this makes us think that our way of working is acceptable despite such simple ideas put into play throughout this entire procedure.

In the enclosed spreadsheet you can see all the details of each of the calculations (and some more studying craters).

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References

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