NEW ESTIMATES FOR THE NUMBER OF LARGE IMPACTS THROUGHOUT EARTH'S HISTORY.

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Introduction: The Earth's impactor Size Frequency Distribution (SFD) is a measure of the number and size of extraterrestrial objects that have struck the Earth. Traditionally we recreate the Earths SFD using the cratering record of the Moon because large craters on Earth are quickly erased by active erosion. Here we present a new method to estimate the size of an impacting body based on the thickness of that global ejecta layer it creates. Using this method and measurements of ejecta layers that are preserved in the geologic record, we create the first impactor SFD for the Earth using only Earth based observations. At impactor sizes larger than ~40km the SFD we obtain is consistent with that implied by cratering on the Moon. This result suggests that the known ejecta layers provide a nearly complete record of very large impacts on Earth in the past 3.5 Gyr. In addition to an impactor SFD, we also present the first estimates of impact velocities based only on ejecta layer data.

Large objects impacting the Earth at typical velocities, greater than ~16km/s, vaporize a significant amount of silicate material. This material is originally shocked to extreme temperatures and pressures; it then expands with velocities comparable to the impact velocity in a large vapor plume or fireball. As this vapor plume cools, spherules or molten droplets condense from the vapor. [1][2][3] The high velocities in the vapor plume lead to global dispersion and deposition of these spherules. For large impacts, with an impactor size larger than ~10km diameter, spherules fall in a layer that completely covers the Earth.[4] The global nature of these layers makes their preservation much more likely than their associated craters, which are destroyed or obscured on short time scales due to tectonic processes and surface weathering.[5] The first spherule layer recognized as impact origin is the 65Myr old Cretaceous–Paleogene (or K-Pg) boundary layer, Alvarez discovered this layer more than ten years before the associated Chicxulub impact structure was recognized.[6][7] Since the discovery of the K-Pg boundary layer, other scientists have found at least 10 similar layers.[5]

There have been several attempts to model the process of spherule formation in the hope that the models may be used to determine the properties of an impacting body from spherule layer data. These simplified models show that spherule size has a strong dependence on the size of an impactor and a weak dependence on the impact velocity.[1][2][8][9] A more detailed model that includes the temperature dependence of surface energy shows the impact velocity, not the size of an impactor, is the main factor that determines the resultant spherule size. [3] This new finding invalidates impactor size estimates based on spherule sizes. Additionally, if impactor size is known, this new model coupled with estimates of spherule sizes can be used to estimate the impact velocity.

Results: In this work, we show that even though we cannot use spherule size to determine the size of an impactor, we can use the thickness of a spherule layer for the same purpose. We have derived the following expression, which gives us the impactor diameter in km as a function of only the reduced spherule layer thickness in cm.

$$D_{imp} = 17\left(\frac{t_r}{\xi}\right)^{\frac{1}{3}} \qquad (1)$$

The reduced thickness $t_r = 2tf_{sp}$, where t is the layer thickness in cm and f_{sp} is the volume fraction of spherules in the layer. Additionally ξ is a factor that has a range from $\xi = 0.5 - 2$. We can test the accuracy of equation 1 by comparing the resulting impactor size to the size as determined by other methods. The K-Pg boundary layer has been found at several sites globally and has a thickness of ~3mm and is ~50% spherules by volume.[4] Using the entire range of ξ we find $D_{imp} = 9.0 - 14\ km$. This is consistent with 10 ± 4 km size of the Chicxulub impactor as determined by Ir fluence and similar estimates obtained from the size of the Chicxulub impact structure.[6][10]

We have compiled data on spherule layer thickness and spherule diameter for all of the known spherule layers in table 1. Assuming that all of the layers are indeed globally uniform vapor condensate spherule layers, and using equation 1 we are able to estimate the size of the impactor responsible for creating the layers based only on the layers thickness. In addition to impactor size we have also calculated impact velocity using the average spherule size and the model put forward by Johnson and Melosh [3]. We include these estimates of impactor size and impact velocity in Table 1. The average estimated impact velocity from all the know spherule layers is $\sim 21.8 \pm 2.3\ km/s$ which is comfortably close to the expected average of ~20.9 km/s.[11]

As previously stated, we traditionally recreate the Earths impactor SFD using the cratering record of the Moon. Now that we have estimates of the size of the impactors responsible for the known spherule layers, we can create an impactor SFD using only Earth based observations. Figure 1 shows both the SFD based on the Moon's cratering record and the SFD based on spherule layer data and the corresponding impactor diameters repoted in Table 1.

Conclusion: Although the history of large impacts on Earth seems novel by itself, the record that spherule layers provide may also allow us to look into the solar system's past. All of the largest impacts with an impactor diameter >30km occurred more than 1.85 Gyr ago. This indicates that the impactor flux was much higher in the past than it is now. Some solar system models that include a so-called E-belt or extended asteroid belt predict a steady decrease of post Late Heavy Bombardment impactor flux with time.[12][13] Our data seems to be consistent with these predictions and may help validate these models, although more thin layers created by impactors with a diameter less than 40 km may need to be found in order to make this claim more robust.

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Table 1:

Name	Age (Gyr)	Impactor Diameter (km)	Impact Velocity (km/s)
S1	3.47	29-53	18.8-21.2
S2	3.26	37-58	17.7-25.6
S3	3.24	41-70	20.6-22.8
S4	3.24	33-53	18.2-22.2
Jeerinah *	2.63	6.3-17	21.9-25.1
Monteville *	2.60-2.65	29-46	20.4-21.4
Carawine *	2.63	49-90	19.9-21.1
Reivilo °	~2.56	17-27	22.4-23.9
Puraburdoo °	2.57	17-27	22.1-23.4
Wittenoom	2.54	6.3-21	21.7-26.1
Brockmann	2.48	31-49	20.1-21.7
Grænsesø	1.85-2.13	46-73	19.1-21.3
K-Pg	0.065	9.0-14	20.4-21.5
Cpx	0.035	4.6-7.3	22.0-27.0

* Possibly from the same impactor

° Possibly from the same impactor

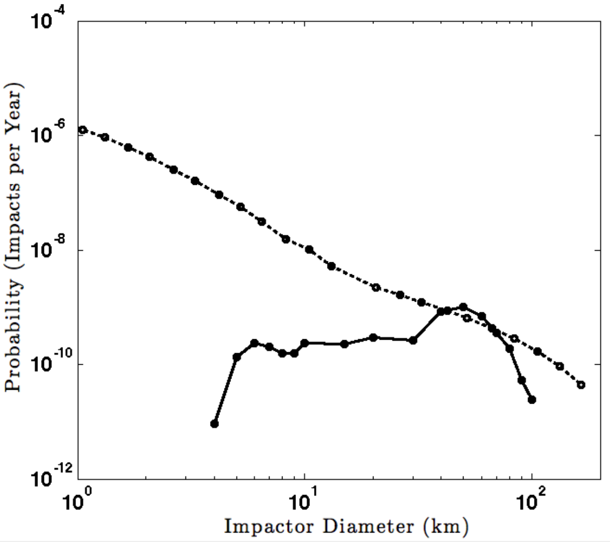

Figure 1:
The impactor size frequency distribution is plotted as the probability in number of impacts per year versus impactor diameter. The solid curve represents the SFD based on the spherule layer data and equation 1. The dashed curve represents the Earth's impactor SFD as inferred from the Moon's cratering record. [11] This impactor size frequency distribution is made in the conventional method using data from table 1 and logarithmic bins with Dr/Dl=sqrt(2) where Dl is the minimum diameter and Dr is the maximum diameter of the bin.[11] To allow a single impactor so span a range of sizes, we define the fractional contribution of any impactor to a bin below as

f = (size range in bin)/(total size range of impator). The total number of impactors in a bin divided by the time since the record began gives the probability of impacts per year. We estimate this time to be ~3.5 Gyr or the age of S1. We also assume that layers indicated as possibly being from the same impactor, are indeed created by the same impactor and that the impactor ranges in size from the smallest to largest reported diameter. For instance we assume that the three spherule beds Jeerinah, Carawine, and Montevile were created by a single impactor which may be anywhere from 6.3 – 90 km in diameter.