Statistical Survey and Analysis of Fireballs and NEOs

Hernández, Giovanna

Escuela de Ciencias Físicas y Matemáticas, Universidad de San Carlos de Guatemala

gioreneeha@gmail.com

Abstract

Studying Near-Earth Objects (NEOs) and fireballs is incredibly important for understanding the potential threats that these objects pose to our planet. This article presents the statistical survey and analysis of fundamental parameters of a sample of NEOs and fireballs obtained from the database of The Center for Near-Earth Object Studies (CNEOS), where it was examined the distributions and correlations of key parameters including impact energy, impact probability, absolute magnitude and geographic location of these phenomena. The results of this study contribute to a deeper understanding of these astronomical objects and their potential impact on Earth.

Introduction

Near-Earth Objects (NEOs) are comets and asteroids that have been nudged by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth's neighborhood. Composed mostly of water ice with embedded dust particles, comets originally formed in the cold outer planetary system while most of the rocky asteroids formed in the warmer inner solar system between the orbits of Mars and Jupiter. [2]

A meteoroid is generally defined as an asteroid or comet fragment that orbits the Sun. Meteors, or "shooting stars", are the visible paths of meteoroids that have entered the Earth's atmosphere at high velocities. A fireball is an unusually bright meteor that reaches a visual magnitude of -3 or brighter when seen at the observer's zenith. [1]

Near-Earth Asteroids (NEAs) are small bodies of the Solar System with perihelion distance $q\ 1.3\ AU$ (Astronomical Units) and aphelion distances $Q\ 0.983\ AU$, whose orbits approach or intersect Earth orbit. [5] Potentially Hazardous Asteroids (PHAs) are a special subset of NEAs that, according to The Center for Near-Earth Object Studies (CNEOS), have an absolute magnitude (H) of 22.0 or less that can come close to the Earth and are large enough to cause significant damage in the event of an impact. [6]

Sentry is a highly automated collision monitoring system that continually scans the most current asteroid catalog for possibilities of future impact with Earth over the next 100 years. Whenever a potential impact is detected it will be analyzed and the results immediately published, except in unusual cases. [3]

Data and Methods

The data about fireballs, NEOs, NEAs and impact probabilities have been collected from the database of The Center for Near-Earth Object Studies (CNEOS) and its monitoring system Sentry. The parameters studied include absolute visual magnitude (H), impact probability, impact energy (kt) and geographic location of fireball objects.

To determine if the impact energy (kt) of fireballs is consistent with some type of distribution it was decided to use the logarithm of the data and then a histogram was made with the counts of the impact energy ($log(kt)$) in intervals of 0.2. With these data, some distribution fit were applied to confirm wich one was more accurate.

At first, the covariance matrix was used to find the linear bond between NEOs absolute magnitude (H) and impact probability, but due to the correlation not being linear, it was discarded. Then proceeded to use Pearson and Spearman correlation coefficients to analyze better the data and determine if a correlation existed and which type it was.

At last, using Gnuplot and Python with various libraries such as pandas, numpy, plotly, a graphic representation of geographic locations with their respective impact energy as the size of the reported events was made.

Results

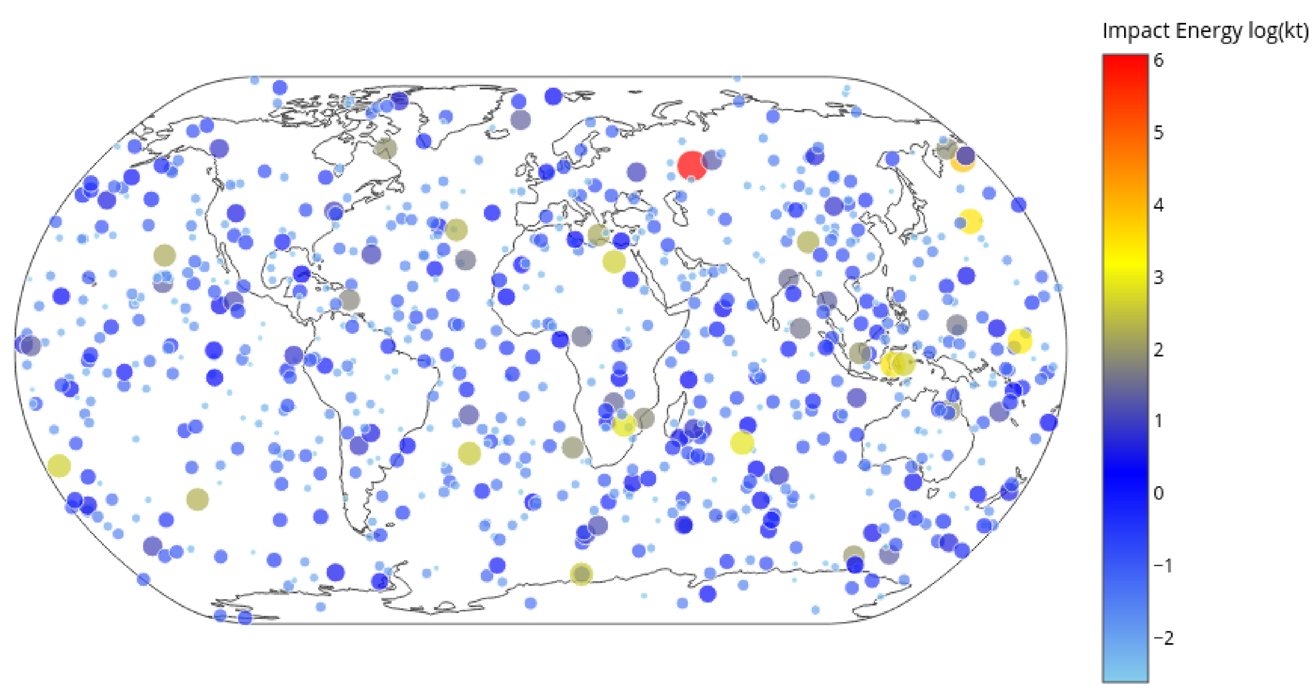

Figure 1: Fireballs reported by US government sensors from April 15, 1988, to May 15, 2024. The size and color of each circle were determined by the logarithm of the impact energy (kt), and the location was determined by the altitude and longitude. All this data was obtained from the database published by NASA's CNEOS at JPL.

As it can be observed in figure 1 and figure 2, the most frequent impact energy is -2.4 to $-2.2\ log(kt)$ which is equivalent to 0.09 and $0.11\ kt$. Little data varies from 1 to $3\ log(kt)$, or its equivalent range 2.72 to $20.01\ kt$ And even more impressive, only one data was far from the rest, it had an impact energy of $440\ kt$. That piece of information was unique among the rest, to the point where it's easy to tell from where the data is. It was the Chelyabinsk meteor of February 15, 2013. It generated infrasound returns, after circling the globe, at distances up to $\sim 85000\ km$, and was detected at 20 infrasonic stations of the global International Monitoring System (IMS). [4] It was surely a unique occurrence.

In figure 2 it can be seen that the fit of a Gaussian distribution was the best, but it had a χ^2 value of $6.37E+03$, which means that the fit had a large variation concerning the original data. With this, it can be said that the fit wasn't precise. On the other hand, the Poisson distribution was also used, but in that case, a fit was not even generated. Same case with Log-normal distribution. That was the reason the Gaussian distribution was selected as the best-fitting one, despite its high variation with the presented data.

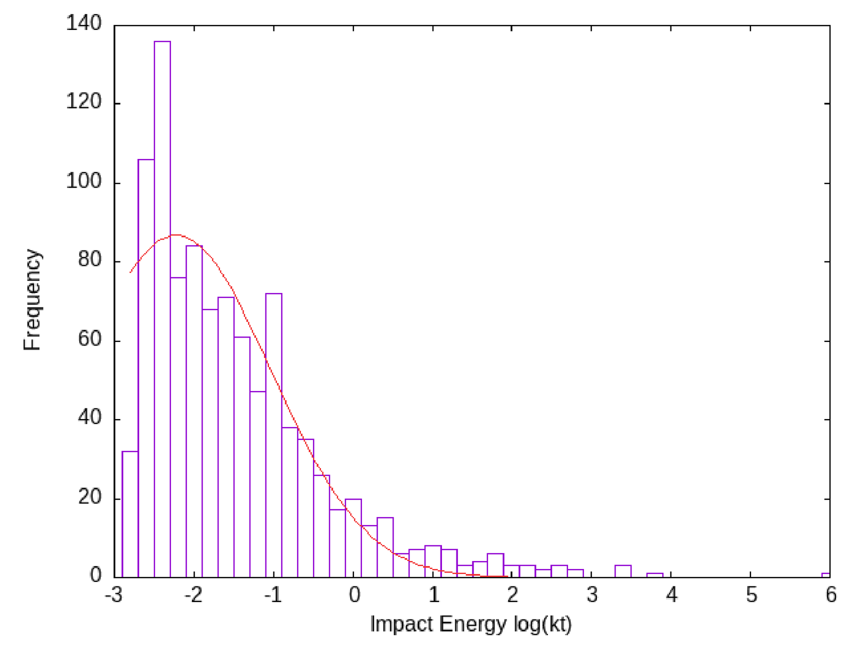

Figure 2: Histogram of logarithmic fireballs impact energy (kt) reported by US government sensors from April 15, 1988, to May 15, 2024. The red line indicates the fit of a Gaussian distribution that was applied to the data. The larger impact energy was of $6\ log(kt)$.

With figure 3, it can be observed the correlation between NEOs impact probability and absolute magnitude (H). To analyze these data, Pearson and Spearman coefficients and the covariance matrix were used.

The diagonal of the covariance matrix had a value of -4.28 for non-cumulative probability and 1.72 for cumulative probability. These results suggest that, in the first case, the two data had a negative correlation, but, in the second case, they had a positive correlation, which is not coherent. For that reason, the covariance matrix was the first method to be discarded.

Then Pearson coefficient was utilized. It gave a correlation of -0.01 for non-cumulative probability and 0.34 for cumulative probability. As in the previous instance, this suggests that in the first case, the two data had a negative correlation and a positive one in the second case. This occurs because both, the covariance matrix and the Pearson coefficient, expect that the data follows a Gaussian or Gaussian-like distribution, which the presented data does not follow.

Finally, Spearman coefficient was used. It returned a correlation of 0.60 for non-cumulative probability and 0.81 for cumulative probability. Unlike the previous ones, this test gave a coherent number, which indicates that the data have a non-linear monotonic correlation.

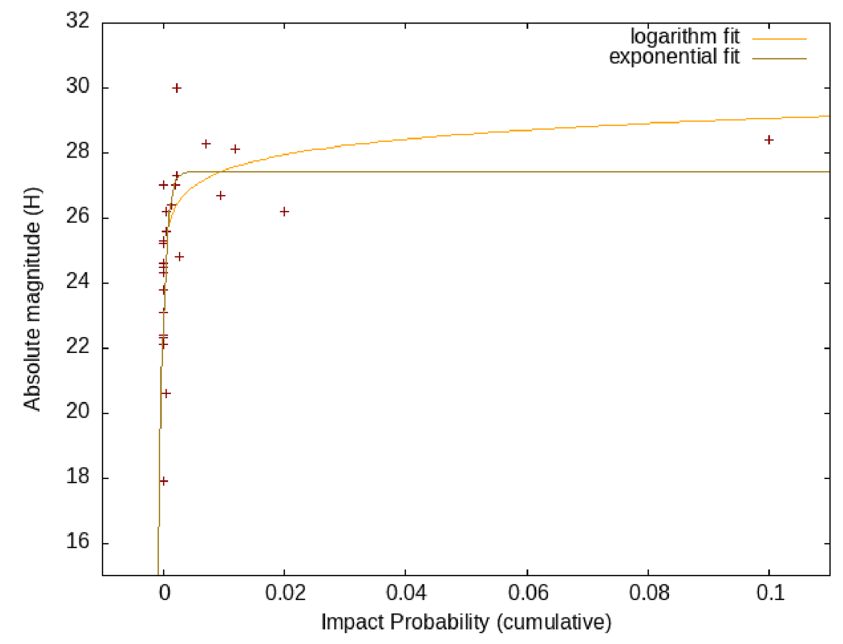

Figure 3: Plot between NEOs impact probability and absolute magnitude (H) obtained from the database published by NASA's CNEOS at JPL. The olive line indicates an exponential fit and the yellow one indicates a logarithmic fit, both were applied to the data.

The exponential fit, corresponding to the olive line in figure 3, had a χ^2 value of 94.07, and the logarithmic fit, corresponding to the yellow line in figure 3, had a χ^2 value of 89.15. In comparison, the logarithmic fit presented fewer variations with the sample data, but it showed that none of them were able to fit correctly the correlation. Due to all of the above, it can be said that there exists a non-linear monotonic correlation between NEO impact probability and absolute magnitude (H), but it isn't enough to fit it into a function either in logarithmic or exponential form.

Also, it can be noted that there exists an inverse correlation between the absolute magnitude (H) and the diameter of astronomical objects. So it can be assumed that the impact probability has a small inverse correlation with the diameter of the NEO. But the correlation isn't strong enough to extrapolate it correctly.

Conclusions

- The most likely impact energy of a fireball is between the range of 0.09 and $0.11\ kt$, being the ones with impact energy between 2.72 and $20.01\ kt$ a rare occurrence and a fireball with impact energy larger than $50\ kt$ a unique event.
- Even though the figure 2 resembles some kind of distribution, the ones that were fitted to the histogram didn't return precise fittings or a fit at all.
- From figure 3 it can be observed that it's unlikely for a PHA to impact Earth. That's because according to CNEOS, the NEA should have an absolute magnitude (H) of 22.0 or less, and the graph shows that these kinds of objects are the ones with the least impact probability.
- It was shown that, according to various correlation coefficients, there exists a small non-linear monotonic relationship between the absolute magnitude (H) and the impact probability of NEO. But it isn't enough to extrapolate it to an inverse relationship between diameter and impact probability.
- Due to the particular correlation between the absolute magnitude (H) and the impact probability found in this study, the data can't be fitted into a function, either in logarithmic or exponential form.
- It can be concluded that the study of NEOs, NEAs, fireballs and more objects of this kind, it's extensive and of great interest to comprehend in a better way the behavior of these objects and their implications for the integrity of the Earth.

References

[1] CNEOS. Fireballs — cneos.jpl.nasa.gov. *https://cneos.jpl.nasa.gov/fireballs/intro.html*. [Accessed 19-05-2024].

[2] CNEOS. NEO Basics — cneos.jpl.nasa.gov. *https://cneos.jpl.nasa.gov/about/basics.html*. [Accessed 19-05-2024].

[3] CNEOS. Sentry: Earth Impact Monitoring — cneos.jpl.nasa.gov. *https://cneos.jpl.nasa.gov/sentry/*. [Accessed 19-05-2024].

[4] Alexis Le Pichon, Lars Ceranna, Christoph Pilger, Pierrick Mialle, David Brown, Pascal Herry, and Nicolas Brachet. The 2013 russian fireball largest ever detected by ctbto infrasound sensors. *Geophysical Research Letters*, 40(14), 2013.

[5] J. Rukmini, G. Raghavendra, S. A. Ahmed, D. Shanti Priya, and Syeda Azeem Unnisa. Statistical survey and analysis of photometric and spectroscopic data on neas. 2016.

[6] Yufan Fane Zhou, Hailiang Li, Zhiyuan Li, and Liyong Zhou. Martians (mars2020, tianwen and so on) would see more potentially hazardous asteroids than earthlings. *https://cneos.jpl.nasa.gov/fireballs/intro.html*, 2024.

Contact Details

Giovanna Hernández - gioreneeha@gmail.com