The Sky is Falling!

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Assumptions

1. The diameter (D) of the asteroid at impact is 1,000 m. Heat and stress while traveling through the Earth's atmosphere would cause some portion to vaporize or burn before impact. However, for an object this large traveling at speeds typical of cosmic objects impacting the earth, one can ignore the deceleration and ablation (loss of mass from the surface of an object due to frictional forces) due to the atmosphere [Steel 1995, 178].
2. The asteroid strikes the earth at the geographic South Pole.
3. The asteroid is spherical.
4. The asteroid is homogeneous with uniform density $\rho = 2.5\ \mathrm{g/cm^3}$; uniform density allows for simple estimates of the mass. The value of ρ is typical of C-type (carbonaceous) asteroids, which make up the majority of the asteroids in the solar system and therefore are the most likely type to strike earth, and also within the typical range of densities of S-type (stony) asteroids, which make up a majority of the asteroids with orbits that cross the Earth's orbit [Morrison and Owen 1996, 103–132].

Preliminary Calculations

Mass of the Asteroid

The mass of the asteroid (M_a) is its density (ρ) multiplied by its volume (V). For a spherical asteroid, the mass is given by

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$$M_a = V\rho = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3\rho.$$

For our asteroid, $D = 1{,}000$ m and $\rho = 2.5\ \mathrm{g/cm^3}$, thus

$$M_a = 1.3 \times 10^{12}\ \mathrm{kg}.$$

Upper and Lower Bounds on Impact Speed

A planet's escape velocity (v_{esc}) is the minimum speed that an object must have to escape the planet. It is calculated by determining the change in potential energy caused by moving an object from the planet's surface to "infinity." To escape the planet, the object's initial kinetic energy must be greater than or equal to the change in potential energy. By symmetry, the escape velocity is also the minimum velocity that an object from beyond the planet can have when it reaches the planet's surface. Thus, the Earth's escape velocity, $v_{\mathrm{esc}} = 11.2\ \mathrm{km/s}$, is a lower bound on the asteroid's impact speed (v_{imp}).

There is also an upper bound on the impact velocity, "a combination of escape velocity, heliocentric orbital velocity, and the velocity of an object just barely bound to the sun at the planet's orbital position." For Earth, this maximum is 72.8 km/s [Melosh 1989, 205]. Thus, the impact velocity is bounded by

$$11.2\ \mathrm{km/s} \le v_{\mathrm{imp}} \le 72.8\ \mathrm{km/s}. \tag{1}$$

Energy Released on Impact

The energy of the collision (E_{imp}), drawn from the kinetic energy of the asteroid, is

$$E_{\mathrm{imp}} = \frac{1}{2} M_a v_{\mathrm{imp}}^2.$$

The impact velocity is bounded and the asteroid's mass is fixed. Applying **(1)**, we have

$$8.2 \times 10^{19}\ \mathrm{J} \le E_{\mathrm{imp}} \le 3.4 \times 10^{21}\ \mathrm{J}. \tag{2}$$

Effects of Impact

Crater Size

The crater from the impact would be roughly parabolic in shape, with a diameter of approximately 10 km and a depth of approximately 1 km [Koeberl and Sharpton 1998]. The pressure is so great in impacts of this sort that the crater forms partially from the vaporization of the target material. At the South Pole, the asteroid would be impacting in ice about 2,600 m thick. It takes considerably lower energies to vaporize ice than rock or soil, therefore we expect that the impact crater would be larger than similar impact craters in other locations.

Melting and Vaporization of Antarctic Polar Ice Cap

Could an asteroid impact at the South Pole melt the Antarctic polar ice cap and drastically changing global sea levels? The ice cap covers 1.32×10^{13} m^2 with average thickness 2,440 m [Ronne 1997]. Thus, there is 3.2×10^{16} m^3 of ice, with mass 2.9×10^{19} kg.

At most, the asteroid impact could create 3.4×10^{21} J. If all the energy were to melt ice, how much ice could be melted?

Assuming that the ice is at $0°$ C, it would take 3.33×10^5 J/kg to melt 1 kg of ice [Wilson and Buffa 1997]. So, at most

$$\frac{3.4 \times 10^{21}}{3.3 \times 10^5} \approx 1 \times 10^{16} \text{ kg}$$

of ice could be melted. This translates to 1×10^4 km^3 of liquid water. The area of the world's oceans is approximately 3.61×10^6 km^2; so if the melted water were evenly distributed across the world's oceans, sea level would rise less than 3 cm. This is not enough to endanger human lives or displace human settlements.

This estimate is an upper bound, since some energy goes into destroying the asteroid on impact; vaporizing part of the asteroid; vaporizing ice; excavating the crater; creating sound, shock, and seismic waves; and heating the air around the impact site. The impact would probably vaporize much of the ice from the impact crater. Assuming that the volume of ice vaporized is equal to the volume of ice in the largest cone that fits in the roughly parabolic crater, the impact would vaporize 2.6×10^{10} m^3 of ice, or 2.4×10^{13} kg of ice. The energy required to melt a kilogram of ice, heat the kilogram of resulting water to $100°$ C, and vaporize the water is 3×10^6 J. Vaporizing so much ice would require 7.2×10^{19} J. This value is within the bounds on the impact energy in **(2)**.

Earthquakes and the Risk of Tsunami

We can estimate the magnitude (Q) of the seismic disturbance (as measured on the Richter scale) from the formula [Melosh 1989, 67]

$$Q = 0.67 \log_{10}(E_{\text{imp}}) - 4.87. \tag{3}$$

The seismic disturbance due to a cosmic impact is not the same as from normal seismic activity. The effect of impact-generated seismic waves is estimated to be an earthquake of one magnitude less than the approximate magnitude generated by impact [Melosh 1989, 67].

For our asteroid, equation **(3)** (using the energy range from **(2)**) tells us that the impact would generate a seismic disturbance ranging in magnitude from 8.5 to 9.6 on the Richter scale (**Figure 1**). Even if the effects are discounted by one magnitude, such an earthquake would cause many human casualties if located in a more-populated part of the world than the South Pole. However, human casualties are negligible because the continent is mostly uninhabited and because Antarctica is large enough that any damage would be limited to Antarctica.

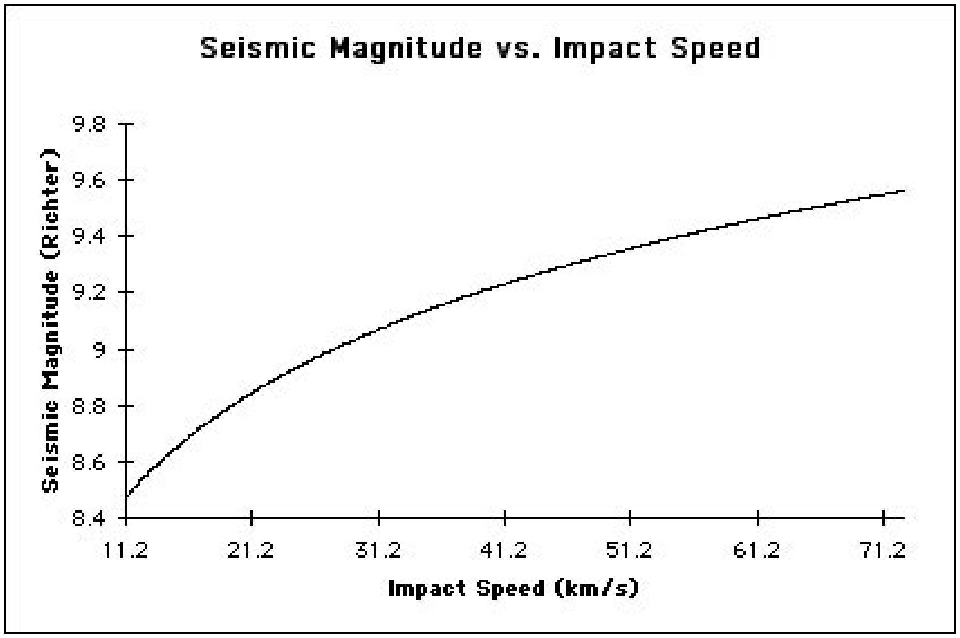

Figure 1. Seismic magnitude vs. impact speed.

Because the impact is at least 500 km from the closest shoreline and 1,500 km from most of the shoreline, the risk of a catastrophic tsunami being generated is negligible. A large percentage of the coast of Antarctica is lined with sheer walls of ice (on the order of 30 m in height). There is indeed a very real danger that the seismic disturbance could cause large fragments to break off, fall into the water, and cause tsunamis. Landslide-generated tsunamis can be large; the 1936 tsunami in Lituya Bay, Alaska, reached a height of 150 m [Hamilton 1998a]. However, they dissipate quickly and are unable to cross the great, transoceanic distances associated with earthquake-generated tsunamis. The greatest risk would be to coastal areas on the southern tip of South America.

Atmospheric Effects

Upon impact, the asteroid would disintegrate. Approximately 10% of the mass, 3.1×10^{11} kg, would be vaporized into submicron particles that would rise to the stratosphere (an altitude of 16 to 48 km) and would remain there for months [Steel 1995, 67]. If dust made up of 1-micron particles were spread evenly in a 1-micron-thick spherical layer at height H above the surface of the earth, it would cover approximately 10% of the surface area of the imaginary sphere and would block 10% of incoming solar radiation. On a very cloudy day, the intensity of light reaching the surface of the earth is roughly 10% of the intensity of light on a clear day [Steel 1995, 66]. A 10% drop in intensity would allow 9 times the intensity of light to reach earth as on a very cloudy day; but over a period of months, such a drop would be significant enough to cause global temperature change.

The ice vaporized on impact would rise into the atmosphere and form clouds. The water vapor in these clouds would eventually fall to earth as rain, increasing the amount of liquid water on the Earth by 8.1×10^{10} m^3. If it all ended up in the world's oceans, the global sea level would rise about 2 cm.

Conclusions

Fear that the ice cap would melt and cause global flooding is unfounded.

Because the asteroid would impact at the South Pole, the dust levels are far less than if the same asteroid impacted in soil and/or rock. Still, enough dust is lifted into the stratosphere to block up to 10% of the sunlight—enough to impact global temperature but far from the threshold where photosynthesis becomes impossible. Reduced light levels and temperature would affect agricultural production, but the impact on the world's food supply would be small; food surpluses in industrialized countries should be able to make up for agricultural losses in other nations.

The ice vaporized from the crater would form clouds and eventually fall to earth in liquid form. But the volume of the water is not large enough to cause large-scale coastal flooding, unless it all falls in a limited area in a limited amount of time. The dust that is larger than a micron and does not reach the stratosphere could still have detrimental effects, such as acid rain. But our model has no way of estimating the amount, location, or effects of possible acid rain.

Because the asteroid hits in Antarctica, the death toll directly due to impact is limited to the few hundred researchers stationed there. These casualties could be eliminated by evacuation if there is enough advance warning.

Strengths and Weaknesses

Our model is successful in that we have quantitative estimates of many of the effects associated with the impact, such as the range of possible impact velocities, the range of possible impact energies, the size of the impact crater, the effect of dust raised by impact in the atmosphere, and the magnitude of seismic disturbance generated by impact. Our model is simple enough that all calculations were performed without resorting to a computer.

The simplicity of our model also brings about some weaknesses. We have no accurate method to estimate how the total impact energy is distributed. We are also unable to determine long-term environmental consequences. Because of the unpredictable nature of atmospheric dynamics, we are unable to develop a model that would show specific locations and amounts of crops affected by dust raised from the impact. Our model predicts no direct loss of human life, but we are unable to take into account human life lost due to effects on food production.

Our model, while not sophisticated, offers intuitive results. Our estimates of crater size, impact energy, and magnitude of seismic disturbance correlate nicely to other models' predictions, such as those of Hamilton [1998b].

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