Catastrophes and Evolution

- Extinction was not widely accepted before 1800.
- Extinction was established as a fact by Georges Cuvier in 1796, and was critical for the spread of uniformitarianism in spite of the fact that Cuvier viewed extinctions as evidence in favor of catastrophism and opposed Lamarckian evolution theories.
- Over 99% of all species that have ever existed are now extinct.
- Extinctions occur at an uneven rate.
- There have been 6 major and many minor (up to 20) extinctions observed in the fossil record. Nearly all divisions among geological eras, eons and periods are marked by extinctions and originations.

**Cambrian-Ordovician transition 488 Myr**  A series of extinctions that eliminated many brachiopods and tribolites.

**Ordovician-Silurian transition 444 Myr**  Second largest extinction.

**Late Devonian 360 Myr**  A series of extinctions near the Devonian-Carboniferous transition, lasted 20 Myr with several pulses.

**Permian-Triassic extinction 251 Myr**  Earth’s largest extinction killed 96% of all marine species and 70% of land species (plants, insects, vertebrates). Ended dominance of mammal-like reptiles and led to dinosaur dominance.

**Triassic-Jurassic extinction 200 Myr**  Last of large amphibians extinguished.

**Cretaceous-Tertiary extinction 65 Myr**  About 50% of all species, including dinosaurs, were extinguished.

**Holocene extinction, now**  About 70% of biologists view the present as a mass extinction, due to human intervention. Not universally accepted as many argue there are significant differences from extinctions.
Major Extinctions

Marine Genus Biodiversity:
Extinction Intensity

Rohde & Muller, Nature, 2005
Theories of Extinctions

- A theory should
  - explain all the losses, not just a few groups like dinosaurs
  - explain why some organisms survived and others didn’t
  - be based on events that actually happened.

- Flood basalt events, triggered by extensive volcanic activity, have been recorded 11 times and each is connected to an extinction event.

- Sea level falls have been recorded 12 times and 7 are associated with extinctions.

- Asteroid impacts producing craters over 100 km wide have been recorded once and associated with a mass extinction. These could produce intense volcanic activity as well as prolong heating or cooling due to deposition of soot and aerosols into atmosphere.

- Asteroid impacts producing craters less than 100 km wide have been recorded over 50 times, but most not connected to any extinctions.

- Other astronomical events, like supernovae and gamma ray bursts, could irradiate the Earth and destroy the ozone layer among other things. It’s been suggested a supernova was connected with the Ordovician-Silurian transition, but this is only weakly supported by evidence.

- Other terrestrial events connected with global warming or cooling, like Snowball Earth or continental drift.
The Late Permian Extinction

Magnetism reveals world-wide glaciations have occurred.
The Late Permian Extinction

Oxygen generated by aerobic photosynthesis eliminated methane and initiated global cooling.
The Cretaceous-Tertiary Boundary Layer

Raton Pass, NM

Gubbio, Italy
Detail of K-T boundary layer
**Cretaceous-Tertiary Extinction**

Available evidence points strongly to an asteroid impact:

**Iridium enhancements**  In 1980, Alvarez, Alvarez, Asaro and Michels discovered that sedimentary layers at the K-T boundary contain concentrations of iridium and other rare-earth elements between 30 and 130 times normal. These elements are rare in the Earth’s crust, having been drained to Earth’s core when the Earth was molten as part of the Earth’s differentiation. But the same elements are correspondingly abundant in asteroids and comets. The amount of the excess iridium suggested an impactor of 10-15 km diameter.

\[
4\pi R^2 d = 4\pi R^3 / 3 \Rightarrow R = (3 R^2 d)^{1/3}
\]

\[
d = 0.1 \text{ cm, } R_\oplus = 6373 \text{ km} \Rightarrow R = 5 \text{ km}
\]

**Spherules**  Droplets of rock melted by high temperatures

**Shocked quartz**  Formed under high pressure conditions

**Soot**  Ashes in amounts consistent with burning most of Earth’s biota

**Worldwide distribution**

**Liklihood**  A 10-km body will impact the Earth about once per 100 million years, and the K-T extinction occurred 65 Myr ago.

**Craters**  Several craters with ages of 65 Myrs found: Chicxulub, Mexico; Boltysh crater in Ukraine; Silverpit crater in the North Sea

**Crater size**  An impactor produces a crater 20 times its own size, so a 10-km impactor makes a 200 km crater. Chicxulub crater is about 180 km in diameter.
Spherule Distribution

Below: Plate tectonic reconstruction of the world 65 million years ago (modified from Izett 1990) with the distribution of shocked quartz grains (yellow dots) found globally in the K/T boundary. The grain sizes vary between 0.11 and 1.25 mm; the biggest are the ones nearest to Chicxulub.

Above: K/T boundary sites found by 1988 in the Gulf of Mexico area of today.
"The brochure didn't say anything about not allowing same sex couples on board."

The real reason dinosaurs became extinct.
Crater Formation

Craters are always circular.

Energy comes from kinetic energy of impactor and is much larger than the equivalent release of chemical energy (TNT).

Impact speed is the Earth’s escape speed plus the original space velocity.
Impact Effects

• Equate kinetic energy of impactor with gravitational potential energy. Establishes an estimate of impact velocity that is equivalent to the Earth’s escape velocity.

\[
\frac{1}{2}mv_{esc}^2 = \frac{GM_{\oplus}}{R_{\oplus}} \implies v_{esc} = \sqrt{\frac{2GM_{\oplus}}{R_{\oplus}}} = 11 \text{ km s}^{-1} \approx 25,000 \text{ mph}
\]

In fact, an impactor is likely to crash with about 50% more velocity.

• The kinetic energy per projectile mass \( m \) is

\[
\frac{1}{2}v^2 = 1.3 \times 10^{12} \text{ erg g}^{-1} \approx 100 \times \text{TNT}.
\]

• A 1 km-diameter projectile has a mass

\[
m = \frac{4\pi}{3}\rho(D/2)^3 = 1.6 \times 10^{15} \text{ g}
\]

which strikes with an energy equivalent to \( 1.6 \times 10^5 \text{ MT of TNT} \).

• A general rule of thumb is that, on the Earth, a meteoroid will create a crater that is about 20 times bigger than itself.

• On the Moon, the crater will be about 12 times the size of the impactor.
Impacts Do Happen!

Comet Shoemaker-Levy 9, 1994

Peekskill, NY, 1992
On September 15 2007 a chondritic meteorite hit near Caranca, Peru and poisoned about 30 villagers that approached the impact site (600 more had provoked psychosomatic ailments). The impact caused boiling of arsenic-contaminated ground water from natural deposits. The local province is turning this into a tourist attraction.
Has No One Been Killed By A Meteorite?

10,700 BC  End of Pleistocene: Great Lakes impacts linked to worldwide deposits of mammal bones and extinctions including wooly mammoths and saber-tooth tigers; disappearance of Clovis Culture

3123 BC  Köfels impact event in Austria; impactor trajectory recorded on a Sumerian clay tablet

2807 BC  Large impact in Indian Ocean caused megatsunamis

2200 BC  Sudden fall of Sumerian civilization linked to asteroid impact

207 BC  Bavarian impact of 0.7 mile diameter asteroid

536 BC  Two impacts off Australia lead to megatsunamis and linked to reduced sunlight and crop failures in China and Mediterranean

580 AD  Fireball near Bordeaux destroys Orleans

1348 AD  Fireballs and earthquake in Carinthia kills 40,000

1430 AD  Chinese fleet of Zhou Man destroyed, more than 173 ships, by comet

1490 AD  Meteorite falls in Chíng-yang, Shaanxi, China, killing more than 10,000

1631 AD  20,000 fatalities from a seige followed by a cataclysmic meteor impact in Magdeburg, Germany

1907 AD  Family killed by meteorite in Hsin-pái, Weng-Li, China

2001 AD  Red rain of Kerala, India, from comet disintegration
Impact Rate


K/T impact

Tunguska

Lattimer, AST 248, Lecture 15 – p.18/25
**Impact Fatality Estimates**

Simulation of 100,000 years duration, keeping worst event per decade

<table>
<thead>
<tr>
<th>Asteroid/ comet diameter (m)</th>
<th># events</th>
<th># fatal events</th>
<th>% Fatal</th>
<th>Average yield (MT)*</th>
<th>Average fatalities*</th>
<th>Annual risk of fatal event</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-99</td>
<td>9792</td>
<td>949</td>
<td>10</td>
<td>18</td>
<td>43 000</td>
<td>1 in 100</td>
</tr>
<tr>
<td>100-199</td>
<td>173</td>
<td>124</td>
<td>72</td>
<td>300</td>
<td>280 000</td>
<td>1 in 800</td>
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<tr>
<td>200-499</td>
<td>31</td>
<td>29</td>
<td>94</td>
<td>2000</td>
<td>700 000</td>
<td>1 in 3500</td>
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<td>500-999</td>
<td>3</td>
<td>3</td>
<td>100</td>
<td>35 000</td>
<td>13 million</td>
<td>1 in 30 000</td>
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<tr>
<td>All</td>
<td>9999</td>
<td>1105</td>
<td>11</td>
<td>170</td>
<td>120 000</td>
<td>1 in 90</td>
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</tbody>
</table>

*per fatal event

Simulation of 1 million years duration, keeping worst event per century

<table>
<thead>
<tr>
<th>Asteroid/ comet diameter (m)</th>
<th># events</th>
<th># fatal events</th>
<th>% Fatal</th>
<th>Average yield (MT)*</th>
<th>Average fatalities*</th>
<th>Annual risk of fatal event</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-99</td>
<td>8563</td>
<td>2619</td>
<td>31</td>
<td>30</td>
<td>92 000</td>
<td>1 in 382</td>
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<tr>
<td>100-199</td>
<td>1065</td>
<td>736</td>
<td>69</td>
<td>300</td>
<td>310 000</td>
<td>1 in 1359</td>
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<tr>
<td>200-499</td>
<td>311</td>
<td>295</td>
<td>95</td>
<td>3900</td>
<td>1.8 million</td>
<td>1 in 3390</td>
</tr>
<tr>
<td>500-999</td>
<td>45</td>
<td>44</td>
<td>98</td>
<td>29 000</td>
<td>14 million</td>
<td>1 in 22 727</td>
</tr>
<tr>
<td>1000-1999</td>
<td>14</td>
<td>14</td>
<td>100</td>
<td>220 000</td>
<td>180 million</td>
<td>1 in 71 429</td>
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<tr>
<td>2000+</td>
<td>2</td>
<td>2</td>
<td>100</td>
<td>2 million</td>
<td>1.7 billion</td>
<td>1 in 500 000</td>
</tr>
<tr>
<td>All</td>
<td>10 000</td>
<td>3710</td>
<td>37</td>
<td>2 600</td>
<td>2 million</td>
<td>1 in 270</td>
</tr>
</tbody>
</table>

*per fatal event
# Fatality Odds For USA

<table>
<thead>
<tr>
<th>Cause of death</th>
<th>Chances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor vehicle accident</td>
<td>1 in 100</td>
</tr>
<tr>
<td>Murder</td>
<td>1 in 300</td>
</tr>
<tr>
<td>Fire</td>
<td>1 in 800</td>
</tr>
<tr>
<td>Firearms accident</td>
<td>1 in 2,500</td>
</tr>
<tr>
<td><strong>Asteroid/comet impact (lower limit)</strong></td>
<td>1 in 3,000</td>
</tr>
<tr>
<td>Electrocution</td>
<td>1 in 5,000</td>
</tr>
<tr>
<td><strong>ASTEROID/COMET IMPACT</strong></td>
<td>1 in 20,000</td>
</tr>
<tr>
<td>Passenger aircraft crash</td>
<td>1 in 20,000</td>
</tr>
<tr>
<td>Flood</td>
<td>1 in 30,000</td>
</tr>
<tr>
<td>Tornado</td>
<td>1 in 60,000</td>
</tr>
<tr>
<td>Venomous bite or sting</td>
<td>1 in 100,000</td>
</tr>
<tr>
<td><strong>Asteroid/comet impact (upper limit)</strong></td>
<td>1 in 250,000</td>
</tr>
<tr>
<td>Fireworks accident</td>
<td>1 in 1 million</td>
</tr>
<tr>
<td>Food poisoning by botulism</td>
<td>1 in 3 million</td>
</tr>
<tr>
<td>Drinking water with EPA limit of TCE*</td>
<td>1 in 10 million</td>
</tr>
</tbody>
</table>

* EPA, Environmental Protection Agency; TCE, trichloroethylene.

C. R. Chapman

Terrorism →
Fatality Rates

C. R. Chapman
Prediction Consequences

Nature of Problem  Mistaken or exaggerated media report of near-miss or near-term predicted impact causes panic and demands for official action.

Probability of Happening  This has already occurred, and is likely to happen again soon. Most likely way of impact hazard becoming of urgent concern to public officials.

Warning Time  Page-one stories develop in hours with officials being totally surprised.


Examples

• Near miss by 100-m asteroid 60,000 km away. Will people believe official statements?

• Mistaken famous astronomer predicts impact in 10 years, but report not withdrawn for days.

• Official IAU prediction of 1-in-a-few-hundred impact possibility later in century; not refined for months.

• Grotesque media hype of one of above cases.

From C. R. Chapman, Southwest Research Institute
Mitigation

- The energy needed to pulverize an impactor that has a kinetic energy of 1 MT is about 0.0001 MT.
- The energy needed to deflect an impactor is about $3 \cdot 10^{-8}$ of that needed to pulverize it. Power of sunlight:

$$P = 4.3 \cdot 10^{16} \left( \frac{R}{1 \text{ km}} \right)^2 \left( \frac{d}{1 \text{ AU}} \right)^{-2} \text{ erg/s}$$

Acceleration: $a = 2P/(Mc)$. Deflection distance: $\Delta = at^2/2$

$$\Delta = \frac{Pt^2}{Mc} = 1.4 \left( \frac{d}{1 \text{ AU}} \right)^{-2} \left( \frac{1 \text{ km}}{r} \right) \left( \frac{t}{1 \text{ yr}} \right)^2 \text{ km}$$

- For $\Delta \simeq 8000$ km, the size of the Earth, $t \simeq 76 \text{ yrs.}$ is needed if the impactor is at a mean distance of 1 AU from the Sun and is about 1 km in radius.
- The space shuttle main engines could deflect a 1-km body with a lead time of about 30 years.
- Delta 2 1st stage rocket could deflect 100-m body with lead time of 6 months.
- Danger of a bomb attack is that it could lead to many impactors producing damage over a wider range with a cumulative effect at least as large if not larger than the original impactor.