

Impact Events, Extinction Events & Risks to Civilization, Humans and Planet Earth

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Chapter- 1

Impact Event



Artist's impression of a major impact event. The collision between Earth and an asteroid a few kilometers in diameter may release as much energy as several million nuclear weapons detonating simultaneously.

An **impact event** is the collision of a large meteorite, asteroid, comet, or other celestial object with the Earth or another planet. Throughout recorded history, hundreds of minor impact events (and exploding bolides) have been reported, with some occurrences causing deaths, injuries, property damage or other significant localised consequences. An impact event in an ocean or sea may create a tsunami (a giant wave), which can cause destruction both at sea and on land near a seashore.

The latest major impact event occurred in Kaali, Estonia about 700 BC.

Impact events have been a plot and background element in science fiction since knowledge of real impacts became established in the scientific mainstream.

Sizes and frequencies



Something undergoing atmospheric entry

Small objects frequently collide with the Earth. There is an inverse relationship between the size of the object and the frequency that such objects hit the earth. Asteroids with a 1 km (0.62 mi) diameter strike the Earth every 500,000 years on average. Large collisions – with 5 km (3 mi) objects – happen approximately once every ten million years. The last known impact of an object of 10 km (6 mi) or more in diameter was at the Cretaceous-Tertiary extinction event 65 million years ago.

Asteroids with diameters of 5 to 10 m (16 to 33 ft) enter the Earth's atmosphere approximately once per year, with as much energy as Little Boy, the atomic bomb dropped on Hiroshima, approximately 15 kilotonnes of TNT. These ordinarily explode in the upper atmosphere, and most or all of the solids are vaporized. Objects with diameters over 50 m (164 ft) strike the Earth approximately once every thousand years, producing explosions comparable to the one known to have detonated above Tunguska in 1908. At least one known asteroid with a diameter of over 1 km (0.62 mi), (29075) 1950 DA, has a possibility of colliding with Earth on March 16, 2880, with a Torino Scale rating of two.

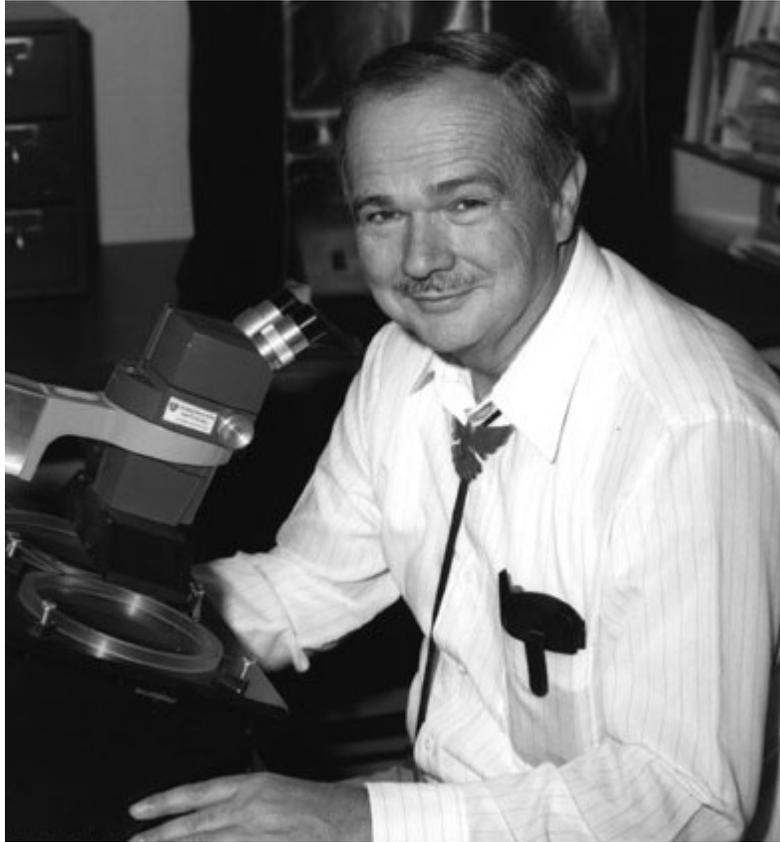
Objects with diameters smaller than 10 m (33 ft) are called meteoroids (or meteorites if they strike the ground). An estimated 500 meteorites reach the surface each year, but only 5 or 6 of these are typically recovered and made known to scientists.

Geology of Earth-impact events

Earth has gone through periods of abrupt and catastrophic change, some due to the impact of large asteroids and comets on the planet. A few of these impacts may have caused massive climate change and the extinction of large numbers of plant and animal species.

The Moon is widely attributed to a huge impact early in Earth's history. Impact events earlier in the history of Earth have been credited with creative as well as destructive events; it has been proposed that the water in the Earth's oceans was delivered by impacting comets, and some have suggested that the origins of life may have been

influenced by impacting objects by bringing organic chemicals or lifeforms to the Earth's surface, a theory known as exogenesis.



Eugene Merle Shoemaker was first to prove that meteor impacts have affected the Earth

These modified views of the Earth's history did not emerge until relatively recently, chiefly due to a lack of direct observations and the difficulty in recognizing the signs of an Earth impact because of erosion and weathering. Large-scale terrestrial impacts of the sort that produced the Barringer Crater, locally known as Meteor Crater, northeast of Flagstaff, Arizona, are rare. Instead, it was widely thought that cratering was the result of volcanism: the Barringer Crater, for example, was ascribed to a prehistoric volcanic explosion (not an unreasonable hypothesis, given that the volcanic San Francisco Peaks stand only 30 miles (48 km) to the west). Similarly, the craters on the surface of the Moon were ascribed to volcanism.

It was not until 1903–1905 that the Barringer Crater was correctly identified as being an impact crater, and it was not until as recently as 1963 that research by Eugene Merle Shoemaker conclusively proved this hypothesis. The findings of late 20th-century space exploration and the work of scientists such as Shoemaker demonstrated that impact cratering was by far the most widespread geological process at work on the solar system's solid bodies. Every surveyed solid body in the solar system was found to be cratered, there was no reason to believe that the Earth had somehow escaped bombardment from

space. The first observation of a major impact event occurred in 1994: the collision of the comet Shoemaker-Levy 9 with Jupiter; to date, no such events have been observed on Earth.

Based on crater formation rates determined from the Earth's closest celestial partner, the Moon, astrogeologists have determined that during the last 600 million years, the Earth has been struck by 60 objects of a diameter of 5 km (3 mi) or more. The smallest of these impactors would release the equivalent of ten million megatons of TNT and leave a crater 95 km (60 mi) across. For comparison, the largest nuclear weapon ever detonated, the Tsar Bomba, had a yield of 50 megatons.

Recent prehistoric impact events

In addition to the extremely large impacts that happen every few tens of millions of years, there are many smaller impacts that occur more frequently but which leave correspondingly smaller traces behind. Due to the strong forces of erosion at work on Earth, only relatively recent examples of these smaller impacts are known. A few of the more famous or interesting examples are:



Aerial view of Barringer Crater in Arizona

- Barringer Crater in the USA, the first crater to be proven the result of an impact, ~50,000 years old.
- the Rio Cuarto craters in Argentina, produced by an asteroid striking Earth at a very low angle, ~10,000 years old.

- the Lonar crater lake in Asia, which now has a flourishing semi-tropical jungle around it, ~52,000 years old (though a study published in 2010 gives a much greater age).
- the Henbury craters in Australia (~5,000 years old), and Kaali craters in Estonia (~2700 years old), apparently produced by objects which broke up before impact.

The Clovis comet hypothesis is a theory that an air burst from a large comet above or even into the Laurentide Ice Sheet north of the Great Lakes set all of the North American continent ablaze around 12,900 years ago. The theory attempts to explain the extinction of most of the large animals in North America and the demise of the North American stone age Clovis culture about at the end of the Pleistocene epoch. Proponents claim the existence of a charred carbon-rich layer of soil found at some 50 Clovis-age sites across the continent. It has been criticized for not being consistent with paleoindian population estimates.

More recent prehistoric impacts are theorized by the Holocene Impact Working Group, including Dallas Abbott of Columbia University's Lamont-Doherty Earth Observatory in Palisades, N.Y. This group points to four enormous chevron sediment deposits at the southern end of Madagascar, containing deep-ocean microfossils fused with metals typically formed by cosmic impacts. All of the chevrons point toward a spot in the middle of the Indian Ocean where newly discovered Burckle crater, 29 km (18 mi) in diameter, or about 25 times larger than Barringer Crater, lies 3,800 m (12,500 ft) below the surface. This group posits that a large asteroid or comet impact c. 2800-3000 BC produced a mega-tsunami at least 180 m (590 ft) high, a catastrophic event that would have affected humanity's cradles of civilization. If this and other recent impacts prove correct, the rate of asteroid impacts is much higher than currently thought.

Years 533–534 CE \pm 2 impact events have been proposed by the dendrochronologist Mike Baillie as a possible cause of several brief (typically 5-10 year) climatic downturns recorded in ancient tree ring patterns. In his book *Exodus to King Arthur: Catastrophic Encounters with Comets*, he highlights four such events and suggests that these might have been caused by the dust veils thrown up by the impact of cometary debris.

Modern impact events

A Chinese record states that 10,000 people were killed in Shanxi Province in 1490 by a hail of "falling stones"; some astronomers surmise that this may describe the breakup of a large asteroid, although they find the number of deaths implausible.

Kamil Crater, discovered from **Google Earth** image review in Egypt, 45 meters in diameter, 10 meters deep is thought to have been formed less than 3,500 years ago in a then-unpopulated region of Western Egypt. It was found February 19, 2009 by V. de Michelle on a Google Earth image of the East Uweinat Desert, Egypt.

The Mahuika crater may have resulted from a modern impact event. The crater is located south of the Snares Islands (120 km (70 mi) southwest of Stewart Island) on the southern

New Zealand shelf and is approximately 20 kilometres (12 mi) wide. Material extracted from Siple Dome ice core melt water indicates that the impact occurred around 1443 A.D.

The Wabar craters in Arabia may have been created sometime during the past few hundred years.



Trees knocked over by the Tunguska blast

The most significant recorded impact in recent times was the Tunguska event, which occurred in Siberia, Russia, in 1908. This incident involved an explosion that was probably caused by the airburst of an asteroid or comet 5 to 10 km (3.1 to 6.2 mi) above the Earth's surface, felling an estimated 80 million trees over 2,150 km² (830 sq mi).

The late Eugene Shoemaker of the U.S. Geological Survey came up with an estimate of the rate of Earth impacts, and suggested that an event about the size of the nuclear weapon that destroyed Hiroshima occurs about once a year. Such events would seem to be spectacularly obvious, but they generally go unnoticed for a number of reasons: the majority of the Earth's surface is covered by water; a good portion of the land surface is uninhabited; and the explosions generally occur at relatively high altitude, resulting in a huge flash and thunderclap but no real damage. Some have been observed. Noteworthy examples include the Sikhote-Alin Meteorite fall in Primorye, far eastern Russia, in 1947, and the Revelstoke fireball of 1965, which occurred over the snows of British Columbia, Canada.

A small number of meteorite falls have been observed with automated cameras and recovered following calculation of the impact point. The first of these was the Pribram meteorite, which fell in Czechoslovakia (now the Czech Republic) in 1959. In this case, two cameras used to photograph meteors captured images of the fireball. The images were used both to determine the location of the stones on the ground and, more significantly, to calculate for the first time an accurate orbit for a recovered meteorite.

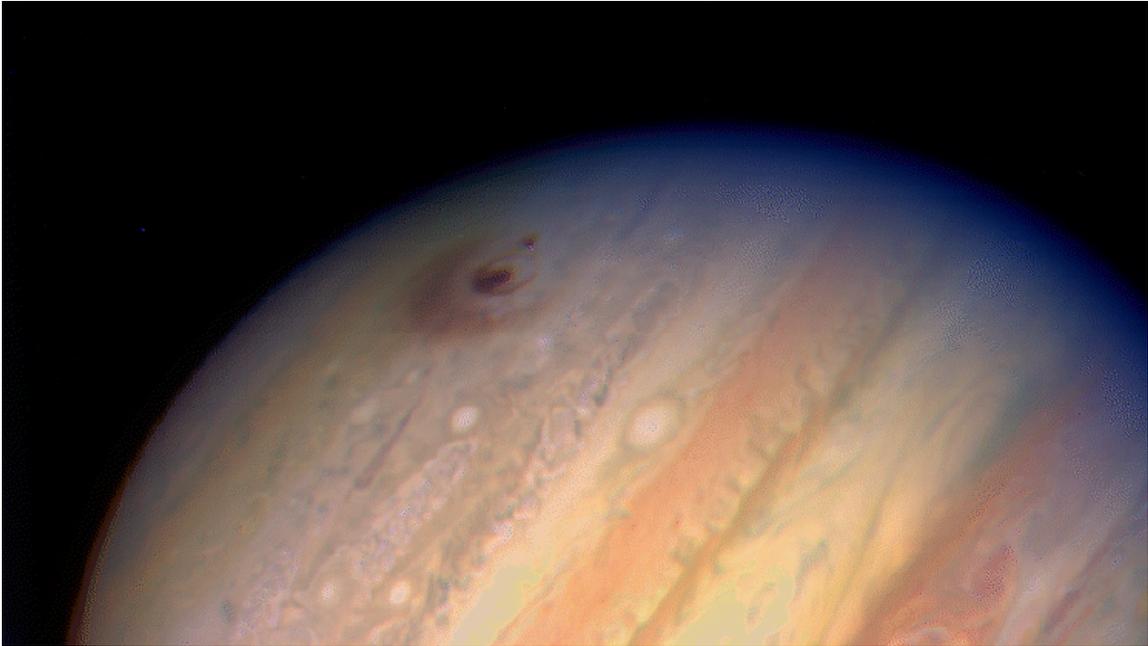
Following the Pribram fall, other nations established automated observing programs aimed at studying infalling meteorites. One of these was the *Prairie Network*, operated by the Smithsonian Astrophysical Observatory from 1963 to 1975 in the midwestern US. This program also observed a meteorite fall, the *Lost City* chondrite, allowing its recovery and a calculation of its orbit. Another program in Canada, the Meteorite Observation and Recovery Project, ran from 1971 to 1985. It too recovered a single meteorite, *Innisfree*, in 1977. Finally, observations by the European Fireball Network, a descendant of the original Czech program that recovered Pribram, led to the discovery and orbit calculations for the Neuschwanstein meteorite in 2002.

The only reported fatality from meteorite impacts is an Egyptian dog that was killed in 1911 by the Nakhla meteorite, although this report is disputed. The meteorites that struck this area were identified in the 1980s as Martian in origin.

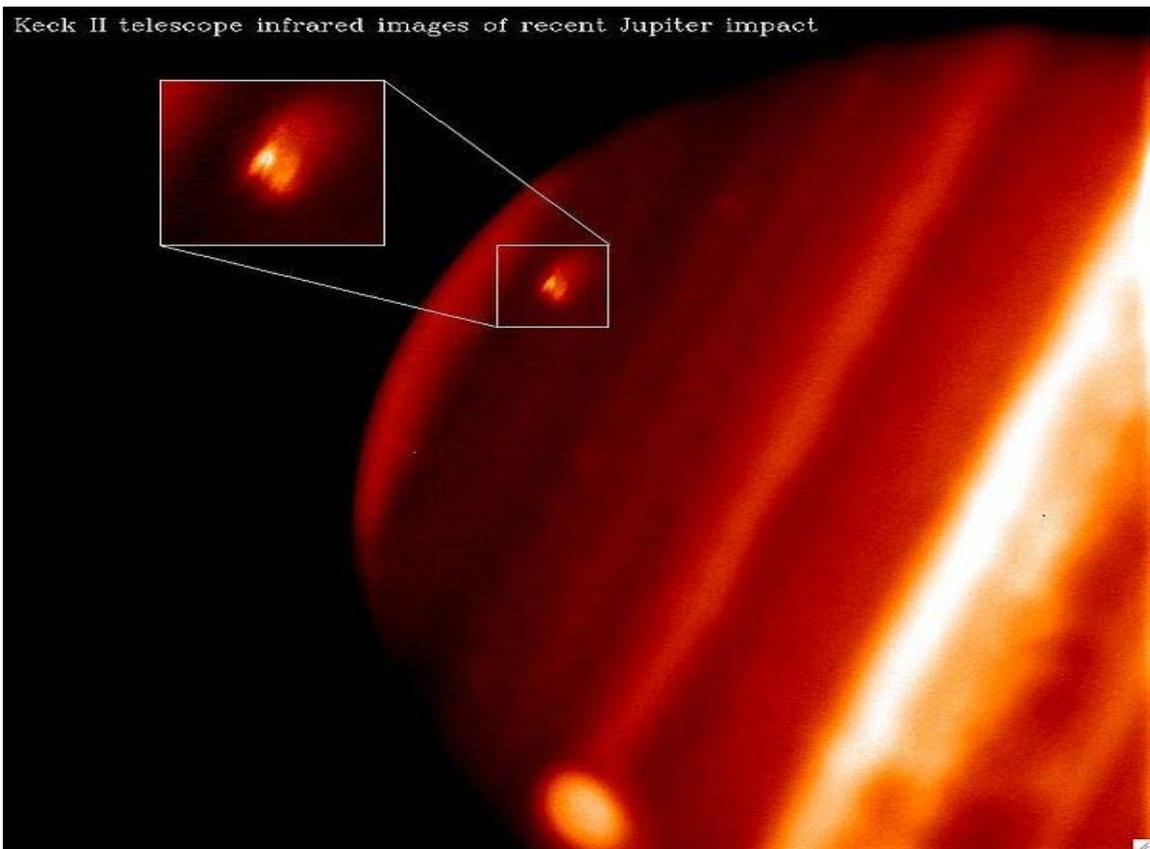
The first known modern case of a human hit by a space rock occurred on November 30, 1954, in Sylacauga, Alabama. There a 4 kg (8.8 lb) stone chondrite crashed through a roof and hit Ann Hodges in her living room after it bounced off her radio. She was badly bruised. Several persons have since claimed to have been struck by 'meteorites' but no verifiable meteorites have resulted.

On August 10, 1972, a meteor which became known as The Great Daylight 1972 Fireball was witnessed by many people moving north over the Rocky Mountains from the U.S. Southwest to Canada. It was filmed by a tourist at the Grand Teton National Park in Wyoming with an 8-millimeter color movie camera. The object was in the range of size from a car to a house and could have ended its life in a Hiroshima-sized blast, but there was never any explosion. Analysis of the trajectory indicated that it never came much lower than 58 km (36 mi) off the ground, and the conclusion was that it had grazed Earth's atmosphere for about 100 seconds, then skipped back out of the atmosphere to return to its orbit around the Sun.

In the dark morning hours of January 18, 2000, a fireball exploded over the city of Whitehorse in the Canadian Yukon at an altitude of about 26 km (16 mi), lighting up the night like day. The meteor that produced the fireball was estimated to be about 4.6 m (15 ft) in diameter and with a weight of 180 tonnes. This blast was also featured on The Science Channel series *Killer Asteroids*, with several witness reports from residents in Atlin, British Columbia.



Comet Shoemaker-Levy 9's scar on Jupiter (dark area near Jupiter's limb)



A picture of the Jupiter 2009 impact event blemish captured by the Keck II telescope and its near-infrared camera at Mauna Kea Observatory, on July 20.

A meteor was observed striking Reisadalen in Nordreisa municipality in Troms County, Norway, on June 7, 2006. Although initial witness reports stated that the resultant fireball was equivalent to the Hiroshima nuclear explosion, scientific analysis places the force of the blast at anywhere from 100-500 tonnes TNT equivalent – around 3% of Hiroshima's yield.

On September 15, 2007, a chondritic meteor crashed near the village of Carancas in southeastern Peru near Lake Titicaca, leaving a water-filled hole and spewing gases across the surrounding area. Many residents became ill, apparently from the noxious gases shortly after the impact.

On November 21, 2009, a fireball was sighted in South Africa by police and traffic cameras. The probable meteor may have landed in a remote area on the Botswana border, and likely made little impact.

Many impact events occur without being observed by anyone on the ground. Between 1975 and 1992, American missile early warning satellites picked up 136 major explosions in the upper atmosphere. In the November 21, 2002, edition of the journal *Nature*, Peter Brown of the University of Western Ontario reported on his study of U.S. early warning satellite records for the preceding 8 years. He identified 300 flashes caused by 1 to 10 m (3 to 33 ft) sized meteors in that time period and estimated the rate of Tunguska-sized events as once in 400 years. Eugene Shoemaker estimated that one of such magnitude occurs about once every 300 years, though more recent analyses have suggested he exaggerated by an order of magnitude.

The 1994 impact of Comet Shoemaker-Levy 9 with Jupiter served as a "wake-up call", and astronomers responded by starting programs such as Lincoln Near-Earth Asteroid Research (LINEAR), Near-Earth Asteroid Tracking (NEAT), Lowell Observatory Near-Earth Object Search (LONEOS) and several others which have drastically increased the rate of asteroid discovery.

In 1998, two comets were observed plunging into the Sun in close succession. The first of these was on June 1 and the second the next day. A video of this, followed by a dramatic ejection of solar gas (supposedly unrelated to the impacts), can be found at the NASA website. Both of these comets evaporated before coming into contact with the surface of the Sun. According to a theory by NASA Jet Propulsion Laboratory scientist Zdeněk Sekanina, the latest impactor to actually make contact with the Sun was the "supercomet" Howard-Koomen-Michels on August 30, 1979.

On October 7, 2008, a meteoroid labeled 2008 TC3 was tracked for 20 hours as it approached Earth and as it fell through the atmosphere and impacted in Sudan. This was the first time an object was detected before it reached the atmosphere and hundreds of pieces of the meteorite were recovered from the Nubian Desert.

On July 19, 2009, a new black spot about the size of Earth was discovered in Jupiter's southern hemisphere by an amateur astronomer. Thermal infrared analysis showed it was

warm and spectroscopic methods detected ammonia. JPL scientists confirmed that another impact event on Jupiter had occurred, probably a small undiscovered comet or other icy body.



Hubble's Wide Field Camera 3 clearly shows the slow evolution of the debris coming from asteroid P/2010 A2, which is thought to be due to a collision with a smaller asteroid.

Between January and May 2010, Hubble's Wide Field Camera 3 took images of an unusual X shape originated in the aftermath of the collision between asteroid P/2010 A2 with a smaller asteroid.

Mass extinctions and impacts

In the past 540 million years there have been five generally-accepted, major mass extinctions that on average extinguished half of all species. One of the largest mass extinction to have affected life on Earth was in the Permian-Triassic, which ended the Permian period 250 million years ago and killed off 90% of all species; life on Earth took 30 million years to recover. The cause of the Permian-Triassic extinction is still matter of debate with the age and origin of proposed impact craters, i.e. the Bedout High structure, hypothesized to be associated with it are still controversial. The last such mass extinction led to the demise of the dinosaurs and coincided with a large meteorite impact; this is the Cretaceous–Tertiary extinction event (also known as the K–T extinction event). There is no definitive evidence of impacts leading to the four other major mass extinctions.

In 1980, physicist Luis Alvarez; his son, geologist Walter Alvarez; and nuclear chemists Frank Asaro and Helen V. Michael from the University of California, Berkeley discovered unusually high concentrations of iridium in a specific layer of rock strata in the Earth's crust. Iridium is an element that is rare on Earth but relatively abundant in many meteorites. From the amount and distribution of iridium present in the 65-million-year-old "iridium layer", the Alvarez team later estimated that an asteroid of 10 to 14 km (6 to 9 mi) must have collided with the earth. This iridium layer at the K–T boundary has been found worldwide at 100 different sites. Multidirectionally shocked quartz (coesite), which is only known to form as the result of large impacts or atomic bomb explosions, has also been found in the same layer at more than 30 sites. Soot and ash at levels tens of thousands times normal levels were found with the above.

Anomalies in chromium isotopic ratios found within the K-T boundary layer strongly support the impact theory. Chromium isotopic ratios are homogeneous within the earth, therefore these isotopic anomalies exclude a volcanic origin which was also proposed as a cause for the iridium enrichment. Furthermore the chromium isotopic ratios measured in the K-T boundary are similar to the chromium isotopic ratios found in carbonaceous chondrites. Thus a probable candidate for the impactor is a carbonaceous asteroid but also a comet is possible because comets are assumed to consist of material similar to carbonaceous chondrites.

Probably the most convincing evidence for a worldwide catastrophe was the discovery of the crater which has since been named Chicxulub Crater. This crater is centered on the Yucatán Peninsula of Mexico and was discovered by Tony Camargo and Glen Pentfield while working as geophysicists for the Mexican oil company PEMEX. What they reported as a circular feature later turned out to be a crater estimated to be 180 km (110 mi) in diameter. Other researchers would later find that the end-Cretaceous extinction event that wiped out the dinosaurs had lasted for thousands of years instead of millions of years as had previously been thought. This convinced the vast majority of scientists that this extinction resulted from a point event that is most probably an extraterrestrial impact and not from increased volcanism and climate change (which would spread its main effect over a much longer time period).

Recently, several craters around the world have been dated to approximately the same age as Chicxulub — for example, the Silverpit crater in the United Kingdom, the Boltysh crater in Ukraine and the Shiva crater near India. This has led to the suggestion that the Chicxulub impact was one of several that occurred almost simultaneously, perhaps due to a disrupted comet impacting the Earth in a similar manner to the collision of Comet Shoemaker-Levy 9 with Jupiter in 1994.

It was the lack of high concentrations of iridium and shocked quartz which has prevented the acceptance of the idea that the Permian extinction was also caused by an impact. During the late Permian all the continents were combined into one supercontinent named Pangaea and all the oceans formed one superocean, Panthalassa. If an impact occurred in the ocean and not on land at all, then there would be little shocked quartz released (since oceanic crust has relatively little silica) and much less material.

Although there is now general agreement that there was a huge impact at the end of the Cretaceous that led to the iridium enrichment of the K-T boundary layer, remnants have been found of other impacts of the same order of magnitude that did not result in any mass extinctions, and there is no clear linkage between an impact and any other incident of mass extinction. Nonetheless it is now widely believed that mass extinctions due to impacts are an occasional event in the history of Earth.

Paleontologists David M. Raup and Jack Sepkoski have proposed that an extinction occurs roughly every 26 million years (though many are relatively minor). This led physicist Richard A. Muller to suggest that these extinctions could be due to a hypothetical companion star to the Sun called Nemesis periodically disrupting the orbits of comets in the Oort cloud, and leading to a large increase in the number of comets reaching the inner solar system where they might hit Earth.

Indeed, in the early history of the Earth (about four billion years ago) bolide impacts were almost certainly common since the solar system contained far more discrete bodies than at present. Such impacts could have included strikes by asteroids hundreds of kilometers in diameter, with explosions so powerful that they vaporized all the Earth's oceans. It was not until this heavy bombardment slackened that life appears to have begun to evolve on Earth.

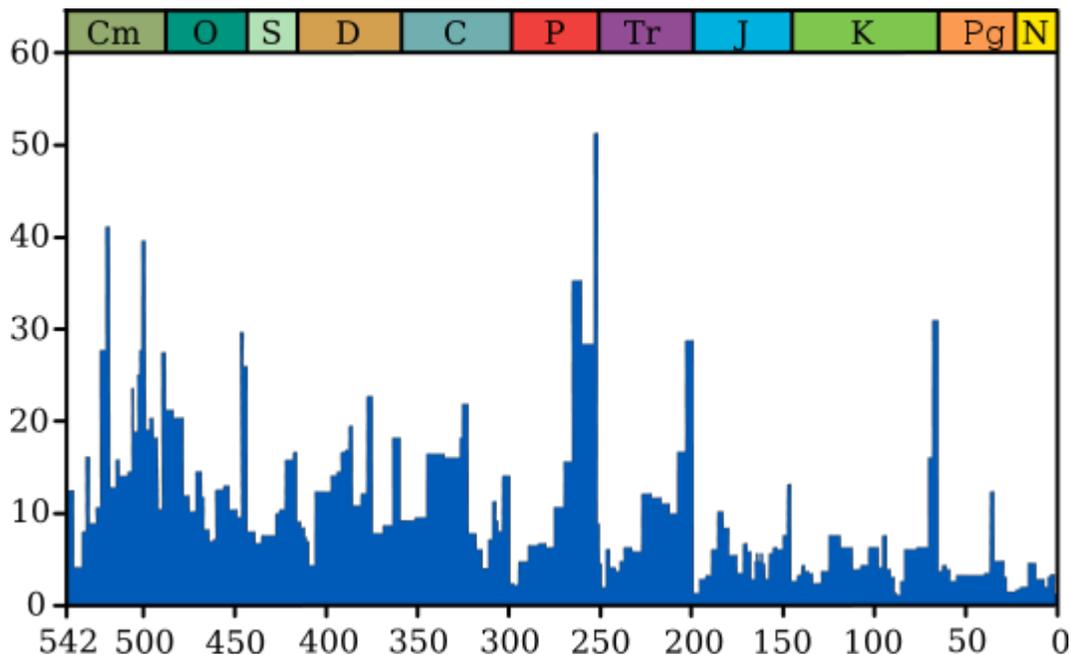
The leading theory of the Moon's origin is the giant impact theory, which states that Earth was once hit by a planetoid the size of Mars; if this theory holds then that impact was almost certainly the largest hit Earth ever suffered.

End of civilization

An impact event is commonly seen as a scenario that would bring about the end of civilization. In 2000, *Discover Magazine* published a list of 20 possible sudden doomsday scenarios with impact event listed as the No. 1 most likely to occur. Until the 1980s this idea was not taken seriously, but all that changed after the discovery of the Chicxulub Crater which was further reinforced by witness to the Comet Shoemaker-Levy 9 event.

Chapter- 2

Extinction Event



Vertical axis - percentage extinction of genera, horizontal axis - mya (millions of years ago)

An **extinction event** (also known as: **mass extinction**; **extinction-level event**, ELE, or **biotic crisis**) is a sharp decrease in the diversity and abundance of macroscopic life. They occur when the rate of extinction increases with respect to the rate of speciation. Because the majority of diversity and biomass on earth is microbial, and thus difficult to measure, mass extinctions have little effect on the *total* diversity and abundance of life, but rather affect the *easily observed, biologically complex* component of the biosphere.

Over 98% of documented species are now extinct, but extinction occurs at an uneven rate. Based on the fossil record, the background rate of extinctions on Earth is about two to five taxonomic families of marine invertebrates and vertebrates every million years. Marine fossils are mostly used to measure extinction rates because of their superior fossil record and stratigraphic range compared to land organisms.

Since life began on Earth, several major mass extinctions have significantly exceeded the background extinction rate. The most recent, the Cretaceous–Tertiary extinction event, occurred 65 million years ago, and has attracted more attention than all others as it marks the extinction of nearly all dinosaur species, which were the dominant animal class of the period. In the past 540 million years there have been five major events when over 50% of animal species died. There probably were mass extinctions in the Archean and Proterozoic Eons, but before the Phanerozoic there were no animals with hard body parts to leave a significant fossil record.

Estimates of the number of major mass extinctions in the last 540 million years range from as few as five to more than twenty. These differences stem from the threshold chosen for describing an extinction event as "major", and the data chosen to measure past diversity.

Major extinction events

The classical "**Big Five**" mass extinctions identified by Jack Sepkoski and David M. Raup in their 1982 paper are widely agreed upon as some of the most significant: End Cretaceous, End Triassic, End Permian, Late Devonian, and End Ordovician. They were originally identified as outliers to a general trend of decreasing extinction rates during the Phanerozoic, but as more stringent statistical tests have been applied to the accumulating data, the "Big Five" cannot be so clearly defined, but rather appear to represent the largest (or some of the largest) of a relatively smooth continuum of extinction events.

These and a selection of other extinction events are outlined below. The articles about individual mass extinctions describe their effects in more detail and discuss theories about their causes.

1. **Cretaceous–Tertiary extinction event** (End Cretaceous or K-T extinction) - 70 to 65 Ma at the Cretaceous.Maastrichtian-Paleogene.Danian transition interval. About 17% of all families, 50% of all genera and 75% of species went extinct. In the seas it reduced the percentage of sessile animals to about 33%. The K-T extinction was rather uneven — some groups of organisms became extinct, some suffered heavy losses and some appear to have been only minimally affected. Mammals and birds emerged as dominant land vertebrates in the age of new life.
2. **Triassic–Jurassic extinction event** (End Triassic) - 205 Ma at the Triassic-Jurassic transition. About 23% of all families and 48% of all genera (20% of marine families and 55% of marine genera) went extinct. Most non-dinosaurian archosaurs, most therapsids, and most of the large amphibians were eliminated, leaving dinosaurs with little terrestrial competition. Non-dinosaurian archosaurs continued to dominate aquatic environments, while non-archosaurian diapsids continued to dominate marine environments. The Temnospondyl lineage of large amphibians also survived until the Cretaceous in Australia (e.g., *Koolasuchus*).
3. **Permian–Triassic extinction event** (End Permian) - 251 Ma at the Permian-Triassic transition. Earth's largest extinction killed 57% of all families and 83% of

all genera (53% of marine families, 84% of marine genera, about 96% of all marine species and an estimated 70% of land species) including insects. The evidence of plants is less clear, but new taxa became dominant after the extinction. The "Great Dying" had enormous evolutionary significance: on land, it ended the primacy of mammal-like reptiles. The recovery of vertebrates took 30 million years, but the vacant niches created the opportunity for archosaurs to become ascendant. In the seas, the percentage of animals that were sessile dropped from 67% to 50%. The whole late Permian was a difficult time for at least marine life, even before the "Great Dying".

4. **Late Devonian extinction** - 360-375 Ma near the Devonian-Carboniferous transition. At the end of the Frasnian Age in the later part(s) of the Devonian Period, a prolonged series of extinctions eliminated about 19% of all families, 50% of all genera and 70% of all species. This extinction event lasted perhaps as long as 20 MY, and there is evidence for a series of extinction pulses within this period.
5. **Ordovician–Silurian extinction event** (End Ordovician) - 440-450 Ma at the Ordovician-Silurian transition. Two events occurred that killed off 27% of all families and 57% of all genera. Together they are ranked by many scientists as the second largest of the five major extinctions in Earth's history in terms of percentage of genera that went extinct.

The older the fossil record gets, the more difficult it is to read. This is because:

- Older fossils are harder to find because they are usually buried at a considerable depth in the rock.
- Dating older fossils is more difficult.
- Productive fossil beds are researched more than unproductive ones, therefore leaving certain periods unresearched.
- Prehistoric environmental disturbances can disturb the deposition process.
- The preservation of fossils varies on land, but marine fossils tend to be better preserved than their sought after land-based counterparts.

It has been suggested that the apparent variations in marine biodiversity may actually be an artifact, with abundance estimates directly related to quantity of rock available for sampling from different time periods. However, statistical analysis shows that this can only account for 50% of the observed pattern, and other evidence (such as fungal spikes) provides reassurance that most widely accepted extinction events are indeed real. A quantification of the rock exposure of Western Europe does indicate that many of the minor events for which a biological explanation has been sought are most readily explained by sampling bias.

Lesser extinctions

Lesser extinction events include:

Period	Start Date	Extinction	date
Precambrian	4567.17	End-Ediacaran extinction	542 Ma
Cambrian	542	End Botomian	517 Ma
		Dresbachian	502 Ma
		Cambro-Ordovician extinction event	488 Ma
Silurian	443.7	Ireviken event	428 Ma
		Mulde event	424 Ma
		Lau event	420 Ma
		End Silurian	416 Ma
Carboniferous	359.2	Middle-Carboniferous extinction	318 Ma
Jurassic	199.6	Toarcian turnover	183 Ma
		End-Jurassic extinction	145.5 Ma
Cretaceous	145.5	Aptian extinction	117 Ma
		Eocene-Oligocene extinction event-	33.9 Ma
Neogene	23.03	Middle Miocene disruption	14.5 Ma
		Quaternary extinction event	50 ka to now
		Holocene extinction	10 ka to now

Evolutionary importance

Mass extinctions have sometimes accelerated the evolution of life on Earth. When dominance of particular ecological niches passes from one group of organisms to another, it is rarely because the new dominant group is "superior" to the old and usually because an extinction event eliminates the old dominant group and makes way for the new one.

For example mammaliformes ("almost mammals") and then mammals existed throughout the reign of the dinosaurs, but could not compete for the large terrestrial vertebrate niches which dinosaurs monopolized. The end-Cretaceous mass extinction removed the non-avian dinosaurs and made it possible for mammals to expand into the large terrestrial vertebrate niches. Ironically, the dinosaurs themselves had been beneficiaries of a previous mass extinction, the end-Triassic, which eliminated most of their chief rivals, the crurotarsans.

Another point of view put forward in the Escalation hypothesis predicts that species in ecological niches with more organism-to-organism conflict will be less likely to survive extinctions. This is because the very traits that keep a species numerous and viable under fairly static conditions become a burden once population levels fall among competing organisms during the dynamics of an extinction event.

Furthermore, many groups which survive mass extinctions do not recover in numbers or diversity, and many of these go into long-term decline, and these are often referred to as

"Dead Clades Walking". So analysing extinctions in terms of "what died and what survived" often fails to tell the full story.

Patterns in frequency

It has been suggested variously that extinction events occurred periodically, every 26 to 30 million years, or that diversity fluctuates episodically every ~62 million years. Various ideas, including the presence of a hypothetical companion star to the sun, oscillations in the galactic plane, or passage through the Milky Way's spiral arms. However, other authors have concluded the data on marine mass extinctions do not fit with the idea that mass extinctions are periodic, or that ecosystems gradually build up to a point at which a mass extinction is inevitable. Many of the proposed correlations have been argued to be spurious. Mass extinctions are thought to result when a long-term stress is compounded by a short term shock. Over the course of the Phanerozoic, individual taxa appear to be less likely to become extinct at any time, which may reflect more robust food webs as well as less extinction-prone species and other factors such as continental distribution. However, even after accounting for sampling bias, there does appear to be a gradual decrease in extinction and origination rates during the Phanerozoic. This may represent the fact that groups with higher turnover rates are more likely to become extinct by chance; or it may be an artefact of taxonomy: families tend to become more speciose, therefore less prone to extinction, over time.

It has also been suggested that the oceans have gradually become more "hospitable" to life over the last 500 million years, and thus less vulnerable to mass extinctions, but susceptibility to extinction at a taxonomic level does not appear to make mass extinctions more or less probable.

Causes

There is still debate about the causes of all mass extinctions. In general, large extinctions may result when a biosphere under long-term stress undergoes a short-term shock. An underlying mechanism appears to be present in the correlation of extinction and origination rates to diversity. High diversity leads to a persistent increase in extinction rate; low diversity to a persistent increase in origination rate. These presumably ecologically-controlled relationships likely amplify smaller perturbations (meteorite impacts, etc) to produce the global effects observed.

Looking for the causes of particular mass extinctions

A good theory for a particular mass extinction should: (i) explain all of the losses, not just focus on a few groups (such as dinosaurs); (ii) explain why particular groups of organisms died out and why others survived; (iii) provide mechanisms which are strong enough to cause a mass extinction but not a total extinction; (iv) be based on events or processes that can be shown to have happened, not just inferred from the extinction.

It may be necessary to consider combinations of causes. For example the marine aspect of the end-Cretaceous extinction appears to have been caused by several processes which partially overlapped in time and may have had different levels of significance in different parts of the world.

Arens and West (2006) proposed a "press / pulse" model in which mass extinctions generally require two types of cause: long-term pressure on the eco-system ("press") and a sudden catastrophe ("pulse") towards the end of the period of pressure. Their statistical analysis of marine extinction rates throughout the Phanerozoic suggested that neither long-term pressure alone nor a catastrophe alone was sufficient to cause a significant increase in the extinction rate.

Most widely supported explanations

Macleod (2001) summarized the relationship between mass extinctions and events which are most often cited as causes of mass extinctions, using data from Courtillot *et al.* (1996), Hallam (1992) and Grieve *et al.* (1996):

- Flood basalt events: 11 occurrences, all associated with significant extinctions But Wignall (2001) concluded that only five of the major extinctions coincided with flood basalt eruptions and that the main phase of extinctions started before the eruptions.
- Sea-level falls: 12, of which seven were associated with significant extinctions.
- Asteroid impacts producing craters over 100 km wide: one, associated with one mass extinction.
- Asteroid impacts producing craters less than 100 km wide: over 50, the great majority not associated with significant extinctions.

The most commonly suggested causes of mass extinctions are listed below.

Flood basalt events

The formation of large igneous provinces by flood basalt events could have:

- produced dust and particulate aerosols which inhibited photosynthesis and thus caused food chains to collapse both on land and at sea
- emitted sulfur oxides which were precipitated as acid rain and poisoned many organisms, contributing further to the collapse of food chains
- emitted carbon dioxide and thus possibly causing sustained global warming once the dust and particulate aerosols dissipated.

Flood basalt events occur as pulses of activity punctuated by dormant periods. As a result they are likely to cause the climate to oscillate between cooling and warming, but with an overall trend towards warming as the carbon dioxide they emit can stay in the atmosphere for hundreds of years.

It is speculated that Massive volcanism caused or contributed to the End-Cretaceous, End-Permian, and End Triassic extinctions.

Sea-level falls

These are often clearly marked by worldwide sequences of contemporaneous sediments which show all or part of a transition from sea-bed to tidal zone to beach to dry land - and where there is no evidence that the rocks in the relevant areas were raised by geological processes such as orogeny. Sea-level falls could reduce the continental shelf area (the most productive part of the oceans) sufficiently to cause a marine mass extinction, and could disrupt weather patterns enough to cause extinctions on land. But sea-level falls are very probably the result of other events, such as sustained global cooling or the sinking of the mid-ocean ridges.

Sea-level falls are associated with most of the mass extinctions, including all of the "Big Five" — End-Ordovician, Late Devonian, End-Permian, End-Triassic, and End-Cretaceous.

A study, published in the journal *Nature* (online June 15, 2008) established a relationship between the speed of mass extinction events and changes in sea level and sediment. The study suggests changes in ocean environments related to sea level exert a driving influence on rates of extinction, and generally determine the composition of life in the oceans.

Impact events

The impact of a sufficiently large asteroid or comet could have caused food chains to collapse both on land and at sea by producing dust and particulate aerosols and thus inhibiting photosynthesis. Impacts on sulfur-rich rocks could have emitted sulfur oxides precipitating as poisonous acid rain, contributing further to the collapse of food chains. Such impacts could also have caused megatsunamis and / or global forest fires.

Most paleontologists now agree that an asteroid did hit the Earth about 65 Ma, but there is an ongoing dispute whether the impact was the sole cause of the extinctions. There is evidence that there was an interval of about 300 ka from the impact to the mass extinction. In 1997, paleontologist Sankar Chatterjee drew attention to the proposed and much larger 600 km (370 mi) Shiva crater and the possibility of a multiple-impact scenario.

In 2007, a hypothesis was put forth that argued the impactor that killed the dinosaurs 65 Ma years ago belonged to the Baptistina family of asteroids. Concerns have been raised regarding the reputed link, in part because very few solid observational constraints exist of the asteroid or family. Indeed, it was recently discovered that 298 Baptistina does not share the same chemical signature as the source of the K-T impact. Although this finding may make the link between the Baptistina family and K-T impactor more difficult to substantiate, it does not preclude the possibility.

In 2010, another hypothesis was offered which implicated the newly-discovered asteroid P/2010 A2, a member of the Flora family of asteroids, as a possible remnant cohort of the K/T impactor.

Sustained and significant global cooling

Sustained global cooling could kill many polar and temperate species and force others to migrate towards the equator; reduce the area available for tropical species; often make the Earth's climate more arid on average, mainly by locking up more of the planet's water in ice and snow. The glaciation cycles of the current ice age are believed to have had only a very mild impact on biodiversity, so the mere existence of a significant cooling is not sufficient on its own to explain a mass extinction.

It has been suggested that global cooling caused or contributed to the End-Ordovician, Permian-Triassic, Late Devonian extinctions, and possibly others. Sustained global cooling is distinguished from the temporary climatic effects of flood basalt events or impacts.

Sustained and significant global warming

This would have the opposite effects: expand the area available for tropical species; kill temperate species or force them to migrate towards the poles; possibly cause severe extinctions of polar species; often make the Earth's climate wetter on average, mainly by melting ice and snow and thus increasing the volume of the water cycle. It might also cause anoxic events in the oceans (see below).

Global warming as a cause of mass extinction is supported by several recent studies.

The most dramatic example of sustained warming is the Paleocene-Eocene Thermal Maximum, which was associated with one of the smaller mass extinctions. It has also been suggested to have caused the Triassic-Jurassic extinction event, during which 20% of all marine families went extinct. Furthermore, the Permian-Triassic extinction event has been suggested to have been caused by warming.

Clathrate gun hypothesis

Millions of years ago

Marine extinction intensity through time. The blue graph shows the apparent *percentage* (not the absolute number) of marine animal genera becoming extinct during any given time interval. It does not represent all marine species, just those that are readily fossilized. The labels of the "Big Five" extinction events are clickable hyperlinks.

The **clathrate gun hypothesis** is the popular name given to the hypothesis that rises in sea temperatures (and/or falls in sea level) can trigger the sudden release of methane from methane clathrate compounds buried in seabeds and permafrost which, because the methane itself is a powerful greenhouse gas, leads to further temperature rise and further

methane clathrate destabilization – in effect initiating a runaway process as irreversible, once started, as the firing of a gun.

In its original form, the hypothesis proposed that the "clathrate gun" could cause abrupt runaway warming in a timescale less than a human lifetime, and might be responsible for warming events in and at the end of the last ice age. This is now thought unlikely.

However there is stronger evidence that runaway methane clathrate breakdown may have caused drastic alteration of the ocean environment and the atmosphere of earth on a number of occasions in the past, over timescales of tens of thousands of years; most notably in connection with the Permian extinction event, when 96% of all marine species became extinct 251 million years ago.

Mechanism



Specific structure of a gas hydrate piece, from the subduction zone off Oregon



Gas hydrate-bearing sediment, from the subduction zone off Oregon

Methane clathrate, also known commonly (albeit incorrectly) as methane hydrate, is a form of water ice that contains a large amount of methane within its crystal structure. Potentially large deposits of methane clathrate have been found under sediments on the ocean floors of the Earth, although there are many orders of magnitudes in between the estimates of various experts. In fact, the existence of vast oceanic methane clathrate formation is uncertain and usually only based on reflective seismology and pieces larger than 10 cm have only been recovered from three sites.

The sudden release of large amounts of natural gas from methane clathrate deposits in runaway climate change could be a cause of past, future, and present climate changes. The release of this trapped methane is a potential major outcome of a rise in temperature; it is thought that this is a main factor in the global warming of 6°C that happened during the end-Permian extinction, as methane is much more powerful as a greenhouse gas than carbon dioxide (despite its atmospheric lifetime of around 12 years, it has a global warming potential of 62 over 20 years and 23 over 100 years). The theory also predicts this will greatly affect available oxygen content of the atmosphere.

Possible release events

Two events possibly linked in this way are the Permian-Triassic extinction event and the Paleocene-Eocene Thermal Maximum. It may also have had a role in the sudden warm-up of "Snowball Earth", 630 million years ago. However, warming at the end of the last ice age is thought not to be due to methane release.

Related mechanism: dissolved methane release

Focusing on the Permian-Triassic boundary, Gregory Ryskin explores the possibility that mass extinction can be caused by an extremely fast, explosive release of dissolved methane (and other dissolved gases such as carbon dioxide and hydrogen sulfide) that accumulated in the oceanic water masses prone to stagnation and anoxia (e.g., in silled basins).

Current outlook

Most deposits of methane clathrate are in sediments too deep to respond rapidly, and modelling by Archer (2007) suggests the methane forcing should remain a minor component of the overall greenhouse effect. Clathrate deposits destabilize from the deepest part of their stability zone, which is typically hundreds of metres below the seabed. A sustained increase in sea temperature will warm its way through the sediment eventually, and cause the deepest, most marginal clathrate to start to break down; but it will typically take of the order of a thousand years or more for the temperature signal to get through.

One exception, however, may be in clathrates associated with the Arctic ocean, where clathrates can exist in shallower water stabilized by lower temperatures rather than higher pressures; these may potentially be marginally stable much closer to the surface of the sea-bed, stabilized by a frozen 'lid' of permafrost preventing methane escape. Recent research carried out in 2008 in the Siberian Arctic has shown millions of tons of methane being released, apparently through perforations in the seabed permafrost, with concentrations in some regions reaching up to 100 times normal. The excess methane has been detected in localized hotspots in the outfall of the Lena River and the border between the Laptev Sea and the East Siberian Sea. Some melting may be the result of geological heating, but more thawing is believed to be due to the greatly increased volumes of meltwater being discharged from the Siberian rivers flowing north. Current methane release has previously been estimated at 0.5 Mt per year. Shakhova et al. (2008) estimate that not less than 1,400 Gt of carbon is presently locked up as methane and methane hydrates under the Arctic submarine permafrost, and 5–10% of that area is subject to puncturing by open taliks. They conclude that "release of up to 50 Gt of predicted amount of hydrate storage [is] highly possible for abrupt release at any time". That would increase the methane content of the planet's atmosphere by a factor of twelve, equivalent in greenhouse effect to a doubling in the current level of CO₂.

In 2008 the United States Department of Energy National Laboratory system and the United States Geological Survey's Climate Change Science Program both identified potential clathrate destabilization in the Arctic as one of four most serious scenarios for abrupt climate change, which have been singled out for priority research. The USCCSP released a report in late December 2008 estimating the gravity of this risk.

Possible outcomes

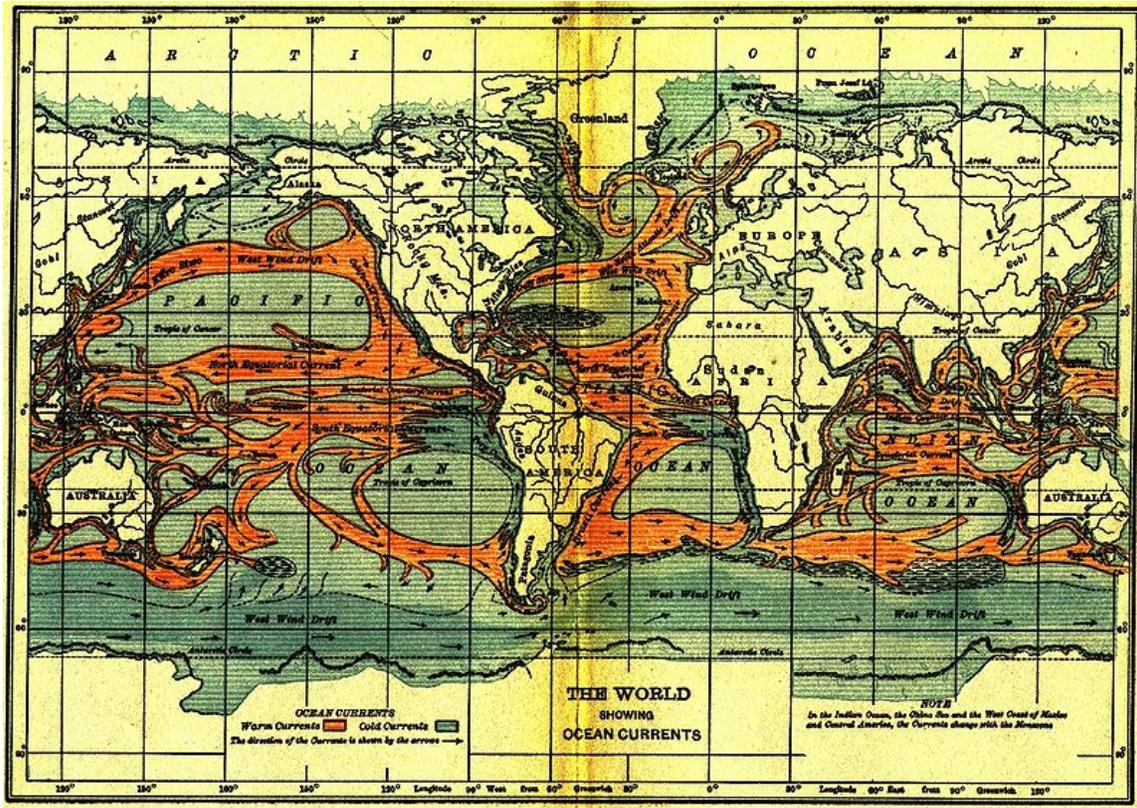
According to Gregory Ryskin, a sudden release of methane from the ocean may lead to either global cooling or global warming. The explosions and burning of methane would produce lots of smoke and dust, which would lead to global cooling. The methane and carbon dioxide would "create the greenhouse effect, which may lead to global warming". Professor Ryskin writes that it is "difficult to predict" whether global cooling or warming would result.

The evolution of dust and smoke, if it caused global cooling, would likely only last a short time before the particulates washed out of the atmosphere. Then the raised levels of methane and the derivative carbon dioxide would take over. The likely result would be an alternating series of extra cold and extra warm years, arguably more devastating to crop production than a trend in one direction or the other.

It may be possible to explain past marine extinctions by the scrubbing effect. If an inert gas is bubbled through water, the surface of each bubble acts as a semi permeable membrane. Gases diffuse across this membrane according to their concentration inside and outside the bubble. The result of bubbling methane through the ocean is to deplete the oxygen dissolved in the water, leading to ocean anoxia.

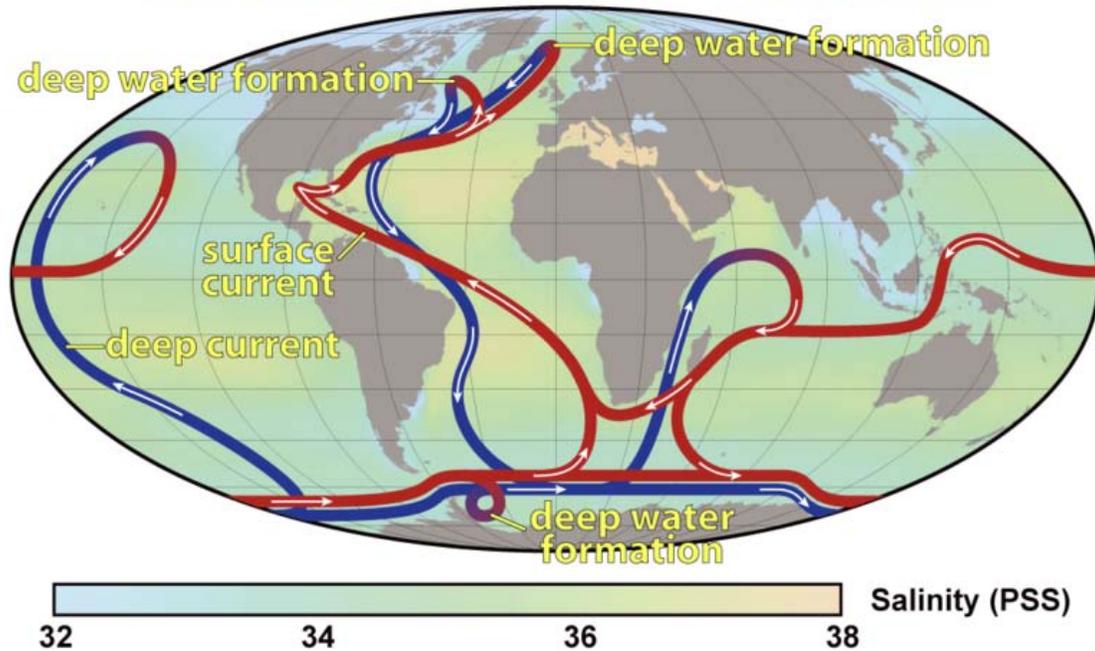
The consequences of a methane-driven oceanic eruption for marine and terrestrial life are likely to be catastrophic. Figuratively speaking, the erupting region "boils over," ejecting a large amount of methane and other gases (e.g., CO₂, H₂S) into the atmosphere, and flooding large areas of land. Whereas pure methane is lighter than air, methane loaded with water droplets is much heavier, and thus spreads over the land, mixing with air in the process (and losing water as rain). The air-methane mixture is explosive at methane concentrations between 5% and 15%; as such mixtures form in different locations near the ground and are ignited by lightning, explosions and conflagrations destroy most of the terrestrial life, and also produce great amounts of smoke and of carbon dioxide. Firestorms carry smoke and dust into the upper atmosphere, where they may remain for several years; the resulting darkness and global cooling may provide an additional kill mechanism. Conversely, carbon dioxide and the remaining methane create the greenhouse effect, which may lead to global warming. The outcome of the competition between the cooling and the warming tendencies is difficult to predict.

Anoxic events



As early as 1911, major oceanic currents were well mapped and understood, albeit without today's understanding of how they affect regional and global climatological conditions.

Thermohaline Circulation



This world perspective on oceanic currents demonstrates the interdependencies of transnational regions on circulating currents.

Oceanic anoxic events or **anoxic events** occur when the Earth's oceans become completely depleted of oxygen (O_2) below the surface levels. Although anoxic events have not happened for millions of years, the geological record shows that they happened many times in the past. Anoxic events may have caused mass extinctions. These mass extinctions were so characteristic they include some of those which geobiologists employ to serve as a time marker in biostratigraphic dating. It is believed oceanic anoxic events are strongly linked to lapses in key oceanic current circulations, to climate warming and greenhouse gases.

Background

Analysis of the geologic records occurring before and after the affected ages are that onsets are rapid and so are recoveries. Both sets of data suggests that a sudden climate threshold or tipping point occurs at about four times the Earth's mean carbon dioxide levels relative to the baseline concentrations of about 280 ppmv in circa 1750. This date is significant in that it is regarded as the beginning of the Industrial age. Strata analysis suggests that in the era when Earth had a predominantly overheated climate, with heavy daily rains and violent storms, the relatively fierce global climate resulted in far heavier erosion which in turn fed more nutrients into the world's waters. At the same time it caused deep water circulation between the poles and the equator to stop in a cataclysmic fashion. This obstruction in oceanic circulation led to 'death in the depths' from oxygen deprivation. The stagnation caused by this lack of circulation could not be offset by

natural processes and became a source of mildly poisonous hydrogen sulfides. The stratified waters would support life in the oxygenated surface layer but the deeper layers became a lethal mixture where life was impossible. The toxic lower layers halted scavenger activity along the organically rich ooze, or sapropel, and all creatures that died in it drifted down and accumulated on the abyssal basins and bottoms. All these life forms unwarily drifting into the anoxic or toxic layers would have died and contributed to the continual accumulation of unicellular microorganisms. The surface layer benefited from an explosion in life, spurred by the increased nutrients from the super-greenhouse conditions, which was then killing itself in waste products. Ironically these deposits of sedimentary organic materials may have accumulated into lipid rich deposits. It is now widely believed that most of today's fossil oil reserves formed in several distinct anoxic events in earth's geologic history.

There are currently several places on earth that are exhibiting the features of anoxic events on a localized level such as algae blooms and localized "dead zones". Dead zones exist off the East Coast of the United States in the Chesapeake Bay, in the Scandinavian strait Kattegat, the Black Sea (which may have been anoxic in its deepest levels for millennia, however), in the northern Adriatic as well as a dead zone off the coast of Louisiana. The current surge of jellyfish worldwide are sometimes regarded as the first stirrings of an anoxic event. Other marine dead zones have appeared in coastal waters of South America, China, Japan, and southeast Australia. A 2008 study counted 405 dead zones worldwide.

This is a recent understanding. This picture was only pieced together during the last three decades. The handful of known and suspected anoxic events have been tied geologically to large-scale production of the world's oil reserves in worldwide bands of black shale in the geologic record. Likewise the high relative temperatures believed linked to so called "super-greenhouse events" Oceanic **anoxic events** were in all likelihood caused or stimulated by extreme episodes of volcanic outgassing. These events contributed to the characteristic elevated carbon dioxide levels four to six times current levels that are attributed to these periods. At even a few degrees warmer, rain forests are extremely vulnerable to fire hazards. These forests have little natural resistance to fires, and some conjecture a critical tipping point. Practically overnight the increase of temperature might have been reached and triggered a huge burn-off of planetary forests. This would have released unprecedented amounts of carbon dioxide into the atmosphere. With a change of mean temperatures of three degrees Celsius, the ice caps melted. This triggered a runaway effect. In the super-greenhouse ecologies—the term meaning average temperature rose to or beyond six degrees above today—the seas were so warm, it is believed the water temperatures at the two poles were in the lower 80s°F (i.e. above 27 °C). The Cretaceous and Jurassic eras world ecologies were essentially ice free, had massive storms driven by warm oceans, and were dying from the double hit of lack of oxygen and toxic hydrogen sulfide accumulations at lower layers because of a shut down in the ocean conveyor belts. In this time, most of the world would experience the highly noxious scent of rotten eggs and the seas would have slowly acquired a deep green hue from the high amounts of algae.

Occurrence

Oceanic anoxic events most commonly occurred during periods of very warm climate characterized by high levels of carbon dioxide (CO₂) and mean surface temperatures probably in excess of 25 °C (77 °F). The Quaternary levels, our current period, are just 13 °C (55 °F) in comparison. Such rises in carbon dioxide may have been in response to a great outgassing of the highly flammable natural gas (methane) some have christened an "oceanic burp". Vast quantities of methane are normally locked into the Earth's crust on the continental plateaus in one of the many deposits consisting of compounds of methane hydrate, a solid precipitated combination of methane and water much like ice. Because the methane hydrates are unstable, save at cool temperatures and high (deep) pressures, scientists have observed smaller "burps" due to tectonic events. Studies suggest the huge release of natural gas could be a major climatological trigger, methane itself being a greenhouse gas many times more powerful than carbon dioxide. However, anoxia was also rife during the Hirnantian (late Ordovician) ice age.

Oceanic anoxic events have been recognized primarily from the already warm Cretaceous and Jurassic Periods, when numerous examples have been documented, but earlier examples have been suggested to have occurred in the late Triassic, Permian, Devonian (Kellwasser event/s), Ordovician and Cambrian.

The Paleocene–Eocene Thermal Maximum (PETM), which was characterized by a global rise in temperature and deposition of organic-rich shales in some shelf seas, shows many similarities to oceanic anoxic events.

Typically, oceanic anoxic events last for under half a million years, before a full recovery.

Consequences

Oceanic anoxic events have had many important consequences. It is believed that they have been responsible for mass extinctions of marine organisms both in the Paleozoic and Mesozoic. The early Toarcian and Cenomanian-Turonian anoxic events correlate with the Toarcian and Cenomanian-Turonian extinction events of mostly marine life forms. Apart from possible atmospheric effects, many deeper-dwelling marine organisms could not adapt to an ocean where oxygen penetrated only the surface layers.

Another, economically significant consequence of oceanic anoxic events is the fact that the prevailing conditions in so many Mesozoic oceans has helped produce most of the world's petroleum and natural gas reserves. During an oceanic anoxic event, the accumulation and preservation of organic matter was much greater than normal, allowing the generation of potential petroleum source rocks in many environments across the globe. Consequently some 70 percent of oil source rocks are Mesozoic in age, and another 15 percent date from the warm Paleogene: only rarely in colder periods were

conditions favorable for the production of source rocks on anything other than a local scale.

Major oceanic anoxic events

Jurassic and Cretaceous

The timeline data of the Jurassic and Cretaceous

The concept of the oceanic anoxic event (OAE) was first proposed in 1976 by Seymour Schlanger (1927–1990) and geologist Hugh Jenkyns and arose from discoveries made by the Deep Sea Drilling Project (DSDP) in the Pacific Ocean. It was the finding of black carbon-rich shales in Cretaceous sediments that had accumulated on submarine volcanic plateaus (Shatsky Rise, Manihiki Plateau), coupled with the fact that they were identical in age with similar deposits cored from the Atlantic Ocean and known from outcrops in Europe—particularly in the geologic record of the otherwise limestone dominated Apennines chain in Italy, that led to the realization that these widespread intervals of similar strata recorded highly unusual "punctuational" conditions in the world ocean during several distinct discrete periods of geological time.

Sedimentological investigations of these organic-rich sediments, which have continued to this day, typically reveal the presence of fine laminations undisturbed by bottom-dwelling fauna, indicating anoxic conditions on the sea floor, believed to be coincident with a low lying poisonous layer of hydrogen sulfide. Furthermore, detailed organic geochemical studies have recently revealed the presence of molecules (so-called biomarkers) that derive from both purple sulfur bacteria and green sulfur bacteria: organisms that required both light and free hydrogen sulfide (H₂S), illustrating that anoxic conditions extended high into the upper water column.

Such sulfidic (or euxinic) conditions, which exist today in many water bodies from ponds to various land surrounded mediterranean seas such as the Black Sea of today, were particularly prevalent in the Cretaceous Atlantic but also characterized other parts of the world ocean. In an ice free sea of these believed super-greenhouse worlds, oceanic waters were as much as 200 meters higher, in some eras. During the time spans in question, the continental plates are believed to have been well separated, and the mountains we know today were (mostly) future tectonic events—meaning the overall landscapes were generally much lower— and even the half super-greenhouse climates would have been eras of highly expedited water erosion carrying massive amounts of nutrients into the world oceans fueling an overall explosive population of microorganisms and their predator species in the oxygenated upper layers.

Detailed stratigraphic studies of Cretaceous black shales from many parts of the world have indicated that two oceanic anoxic events were particularly significant in terms of their impact on the chemistry of the oceans, one in the early Aptian (~120 Ma), sometimes called the Selli Event (or OAE 1a) after the Italian geologist, Raimondo Selli (1916–1983), and another at the Cenomanian–Turonian boundary (~93 Ma), sometimes

called the Bonarelli Event (or OAE 2) after the Italian geologist, Guido Bonarelli (1871–1951).

- Insofar as the Cretaceous OAEs can be represented by type localities, it is the striking outcrops of laminated black shales within the vari-colored claystones and pink and white limestones near the town of Gubbio in the Italian Apennines that are the best candidates.
- The 1-meter thick black shale at the Cenomanian–Turonian boundary that crops out near Gubbio is termed the ‘Livello Bonarelli’ after the man who first described it in 1891.

More minor oceanic anoxic events have been proposed for other intervals in the Cretaceous (in the Valanginian, Hauterivian, Albian and Coniacian–Santonian stages), but their sedimentary record, as represented by organic-rich black shales, appears more parochial, being dominantly represented in the Atlantic and neighboring areas, and some researchers relate them to particular local conditions rather than being forced by global change.

The only oceanic anoxic event documented from the Jurassic took place during the early Toarcian (~183 Ma). Because no DSDP or ODP (Ocean Drilling Program) cores have recovered black shales of this age – there being little or no Toarcian ocean crust remaining in the world ocean – the samples of black shale primarily come from outcrops on land. These outcrops, together with material from some commercial oil wells, are found on all major continents and this event seems similar in kind to the two major Cretaceous examples.

Mechanism

Temperatures throughout the Jurassic and Cretaceous are generally thought to have been relatively warm, and consequently dissolved oxygen levels in the ocean were lower than today - making anoxia easier to achieve. However, more specific conditions are required to explain the short-period (half a million years or less) oceanic anoxic events. Two hypotheses, and variations upon them, have proved most durable.

One hypothesis suggests that the anomalous accumulation of organic matter relates to its enhanced preservation under restricted and poorly oxygenated conditions, which themselves were a function of the particular geometry of the ocean basin: such a hypothesis, although readily applicable to the young and relatively narrow Cretaceous Atlantic (which could be likened to a large-scale Black Sea, only poorly connected to the World Ocean), fails to explain the occurrence of coeval black shales on open-ocean Pacific plateaus and shelf seas around the world. There are suggestions, again from the Atlantic, that a shift in oceanic circulation was responsible, where warm, salty waters at low latitudes became hypersaline and sunk to form an intermediate layer, at 500 to 1,000 m (1,640 to 3,281 ft) depth, with a temperature of 20 °C (68 °F) to 25 °C (77 °F).

The second hypothesis suggests that oceanic anoxic events record a major change in the fertility of the oceans that resulted in an increase in organic-walled plankton (including bacteria) at the expense of calcareous plankton such as coccoliths and foraminifera.

Such an accelerated flux of organic matter would have expanded and intensified the oxygen minimum zone, further enhancing the amount of organic carbon entering the sedimentary record. Essentially this mechanism assumes a major increase in the availability of dissolved nutrients such as nitrate, phosphate and possibly iron to the phytoplankton population living in the illuminated layers of the oceans.

For such an increase to occur would have required an accelerated influx of land-derived nutrients coupled with vigorous upwelling, requiring major climate change on a global scale. Geochemical data from oxygen-isotope ratios in carbonate sediments and fossils, and magnesium/calcium ratios in fossils, indicate that all major oceanic anoxic events were associated with thermal maxima, making it likely that global weathering rates, and nutrient flux to the oceans, were increased during these intervals. Indeed, the reduced solubility of oxygen would lead to phosphate release, further nourishing the ocean and fuelling high productivity, hence a high oxygen demand - sustaining the event through a positive feedback.

Here is another way of looking at oceanic anoxic events. Assume that the earth releases a huge volume of carbon dioxide during an interval of excessive volcanism; global temperatures rise due to the greenhouse effect; global weathering rates and fluvial nutrient flux increase; organic productivity in the oceans increases; organic-carbon burial in the oceans increases (OAE begins); carbon dioxide is drawn down (inverse greenhouse effect); global temperatures fall, and the ocean-atmosphere system returns to equilibrium (OAE ends).

In this way, an oceanic anoxic event can be viewed as the Earth's response to the injection of excess carbon dioxide into the atmosphere and hydrosphere. One test of this notion is to look at the age of large igneous provinces (LIPs), the extrusion of which would presumably have been accompanied by rapid effusion of vast quantities of volcanogenic gases such as carbon dioxide. Intriguingly, the age of three LIPs (Karoo-Ferrar flood basalt, Caribbean large igneous province, Ontong Java Plateau) correlates uncannily well with that of the major Jurassic (early Toarcian) and Cretaceous (early Aptian and Cenomanian-Turonian) oceanic anoxic events, indicating that a causal link is feasible.

Paleozoic anoxia

The boundary between the Ordovician and Silurian periods is marked by repetitive periods of anoxia, interspersed with normal, oxic conditions. In addition, anoxic periods are found during the Silurian. These anoxic periods occurred at a time of low global temperatures (although CO₂ levels were high), in the midst of a glaciation.

Jeppsson (1990) proposes a mechanism whereby the temperature of polar waters determines the site of formation of downwelling water. If the high latitude waters are below 5 °C (41 °F), they will be dense enough to sink; as they are cool, oxygen is highly soluble in their waters, and the deep ocean will be oxygenated. If high latitude waters are warmer than 5 °C (41 °F), their density is too low for them to sink below the cooler deep waters. Therefore thermohaline circulation can only be driven by salt-increased density, which tends to form in warm waters where evaporation is high. This warm water can dissolve less oxygen, and is produced in smaller quantities, producing a sluggish circulation with little deep water oxygen. The effect of this warm water will propagate through the ocean, and the warmer water has the additional effect of reducing the amount of CO₂ which can be stored in the oceans - causing the release of large quantities to the atmosphere in a short time - tens or thousands of years. The warm waters would also initiate the release of clathrates, further increasing both atmospheric temperature and basin anoxia. Similar positive feedbacks operate during cold-pole episodes, amplifying their cooling effects.

The periods with cold poles are termed "P-episodes" (short for *primo*), and are characterised by bioturbated deep oceans, a humid equator and higher weathering rates, and terminated by extinction events - for example, the Ireviken and Lau events. The inverse is true for the warmer, oxic "S-episodes" (*secundo*), where deep ocean sediments are typically graptolitic black shales. A typical cycle of *secundo-primo* episodes and ensuing *event* typically lasts around 3 Ma.

The duration of events is so long compared to their onset because the positive feedbacks must be overwhelmed. Carbon content in the ocean-atmosphere system is affected by changes in weathering rates, which in turn is dominantly controlled by rainfall. Because this is inversely related to temperature in Silurian times, carbon is gradually drawn down during warm (high CO₂) S-episodes, while the reverse is true during P-episodes. On top of this gradual trend is overprinted the signal of Milankovic cycles, which ultimately trigger the switch between P- and S- episodes.

These events become longer during the Devonian; the enlarging land plant biota probably acted as a large buffer to carbon dioxide concentrations.

The end-Ordovician Hirnantian event may alternatively be a result of algal blooms, caused by sudden supply of nutrients through wind-driven upwelling or an influx of nutrient-rich meltwater from melting glaciers, which by virtue of its fresh nature would also slow down oceanic circulation.

Atmospheric effects

A model put forward by Lee Kump, Alexander Pavlov and Michael Arthur in 2005 suggests that oceanic anoxic events may have been characterized by upwelling of water rich in highly toxic hydrogen sulfide gas which was then injected into the atmosphere. This phenomenon would likely have poisoned plants and animals and caused mass extinctions. Furthermore, it has been proposed that the hydrogen sulfide rose to the upper

atmosphere and attacked the ozone layer, which normally blocks the deadly ultraviolet radiation of the Sun. The increased UV radiation caused by this ozone depletion would have amplified the destruction of plant and animal life. Fossil spores from strata recording the Permian extinction show deformities consistent with UV radiation. This evidence, combined with fossil biomarkers of green sulfur bacteria, indicates that this process could have played a role in that mass extinction event, and possibly other extinction events. The trigger for these mass extinctions appears to be a warming of the ocean caused by a rise of carbon dioxide levels to about 1000 parts per million.

Hydrogen sulfide emissions from the seas

Kump, Pavlov and Arthur (2005) have proposed that during the Permian-Triassic extinction event the warming also upset the oceanic balance between photosynthesising plankton and deep-water sulfate-reducing bacteria, causing massive emissions of hydrogen sulfide which poisoned life on both land and sea and severely weakened the ozone layer, exposing much of the life that still remained to fatal levels of UV radiation.

Oceanic overturn

Oceanic overturn is a disruption of thermo-haline circulation which lets surface water (which is more saline than deep water because of evaporation) sink straight down, bringing anoxic deep water to the surface and therefore killing most of the oxygen-breathing organisms which inhabit the surface and middle depths. It may occur either at the beginning or the end of a glaciation, although an overturn at the start of a glaciation is more dangerous because the preceding warm period will have created a larger volume of anoxic water.

Unlike other oceanic catastrophes such as regressions (sea-level falls) and anoxic events, overturns do not leave easily-identified "signatures" in rocks and are theoretical consequences of researchers' conclusions about other climatic and marine events.

It has been suggested that oceanic overturn caused or contributed to the late Devonian and Permian-Triassic extinctions.

A nearby nova, supernova or gamma ray burst

A nearby gamma ray burst (less than 6000 light years away) could sufficiently irradiate the surface of Earth to kill organisms living there and destroy the ozone layer in the process. From statistical arguments, approximately one gamma ray burst would be expected to occur close to Earth in the last 540 million years. A proposal that a supernova or gamma ray burst had caused a mass extinction would also have to be backed up by astronomical evidence of such an explosion at the right place and time.

It has been suggested that a supernova or gamma ray burst caused the End-Ordovician extinction.

Continental drift

Movement of the continents into some configurations can cause or contribute to extinctions in several ways: by initiating or ending ice ages; by changing ocean and wind currents and thus altering climate; by opening seaways or land bridges which expose previously isolated species to competition for which they are poorly-adapted (for example, the extinction of most of South America's native ungulates and all of its large metatherians after the creation of a land bridge between North and South America). Occasionally continental drift creates a super-continent which includes the vast majority of Earth's land area, which in addition to the effects listed above is likely to reduce the total area of continental shelf (the most species-rich part of the ocean) and produce a vast, arid continental interior which may have extreme seasonal variations.

It is widely thought that the creation of the super-continent Pangaea contributed to the End-Permian mass extinction. Pangaea was almost fully formed at the transition from mid-Permian to late-Permian, and the "Marine genus diversity" diagram at the top shows a level of extinction starting at that time which might have qualified for inclusion in the "Big Five" if it were not overshadowed by the "Great Dying" at the end of the Permian.

Plate tectonics

Plate tectonics is the mechanism which drives many of the possible causes of mass extinctions, especially volcanism and continental drift. So it is implicated in many extinctions, but in each case it is necessary to specify which manifestations of plate tectonics were involved.

Other hypotheses

Many other hypotheses have been proposed, such as the spread of a new disease, the Shiva hypothesis, or simple out-competition following an especially successful biological innovation. But all have been rejected, usually for one of the following reasons: they require events or processes for which there is no evidence; they assume mechanisms which are contrary to the available evidence; they are based on other theories which have been rejected or superseded.

Effects

The impact of mass extinction events varied widely. The worst event, the Permian-Triassic Extinction Event, devastated life on earth and is estimated to have killed off over 90% of species. Life on Earth seemed to recover quickly after this extinction, but this was mostly in the form of disaster taxa, such as the hardy *Lystrosaurus*. The most recent research indicates that the specialized animals that formed complex ecosystems, with high biodiversity, complex food webs and a variety of niches, took much longer to recover. It is thought that this long recovery was due to the successive waves of extinction which inhibited recovery, as well as to prolonged environmental stress to organisms which continued into the Early Triassic. Recent research indicates that

recovery did not begin until the start of the mid-Triassic, 4M to 6M years after the extinction; and some writers estimate that the recovery was not complete until 30M years after the P-Tr extinction, i.e. in the late Triassic.

Chapter- 3

Risks to Civilization, Humans and Planet Earth

Risks to civilization, humans, and planet Earth are existential risks that could threaten humankind as a whole, have adverse consequences for the course of human civilization, or even cause the end of planet Earth. The concept is expressed in various phrases such as "End of the World", "Doomsday", "Ragnarök", "Judgment Day", "Armageddon", "the Apocalypse", "Yawm al-Qiyāmah" and others.

Types of risks

Various risks exist for humanity, but not all are equal. Risks can be roughly categorized into six types based on the scope (personal, regional, global) and the intensity (endurable or terminal). The following chart provides some examples:

Typology of risk		
	Endurable	Terminal
Global	Plate tectonics	Nearby gamma-ray burst
Regional	Flash flooding	Permanent submersion
Personal	Assault	Death

The risks discussed here are at least Global and Terminal in intensity. These types of risks are ones where an adverse outcome would either annihilate intelligent life on Earth, or permanently and drastically reduce its potential. Jamais Cascio made an alternative classification system.

Future scenarios

Many scenarios have been suggested. Some that will almost certainly end life on Earth are certain to occur, but on a very long timescale. Others are likely to happen on a shorter timescale, but will probably not completely destroy civilization. Still others are extremely unlikely, and may even be impossible. For example, Nick Bostrom writes:

Some foreseen hazards (hence not members of the current category) which have been excluded from the list on grounds that they seem too unlikely to cause a global terminal disaster are: solar flares, supernovae, black hole explosions or mergers, gamma-ray bursts, galactic center outbursts, buildup of air pollution, gradual loss of human fertility, and various religious doomsday scenarios.

The distant future

There are a number of cosmological theories as to the universe's ultimate fate that exclude the indefinite continuation of life. Most involve time periods and distant futures much greater than the current 13.7-billion-year age of the universe. A long-established and widely accepted theory is the eventual heat death of the universe.

The theory of stellar evolution predicts that our Sun will exhaust its hydrogen core and become a red giant in about 5 billion years, becoming thousands of times more luminous and losing roughly 30% of its current mass. Ignoring tidal effects, the Earth would then orbit 1.7 AU (250,000,000 km) from the Sun at its maximum radius. This would allow the Earth to escape being enveloped by the Sun's now expanded and thin outer atmosphere, though most life, if not all, would perish due to the Sun's proximity. However, a more recent study suggests that the Earth's orbit will decay due to the effects of tidal drag, causing it to enter the Sun's expanded atmosphere and be destroyed in 7.6 billion years. Before being swallowed by the Sun, the Earth's oceans would evaporate, and the Earth would finally be destroyed by tidal forces.

Meteorite impact

Earth has collided with several large asteroids in recent geological history. The Cretaceous-Tertiary asteroid, for example, is theorized to have caused the extinction of the dinosaurs 65 million years ago. If such an object struck Earth it could have a serious impact on civilization. It is even possible that humanity would be completely destroyed; for this to occur the asteroid would need to be at least 1 km (0.62 miles) in diameter, but probably between 3 and 10 km (2–6 miles). Asteroids with a 1 km diameter have impacted the Earth on average once every 500,000 years. Larger asteroids are less common. So-called Near-Earth asteroids are regularly being observed.

1.4 million years from now the star Gliese 710 is expected to cause an increase in the number of meteoroids in the vicinity of Earth by passing within 1.1 light years of the Sun. Some models predict that this will cause a large number of comets from the Oort cloud to impact Earth, whereas other models predict only a 5% increase in the rate of impact.

Other cosmic threats

A number of other scenarios have been suggested. Massive objects, e.g., a star, large planet or black hole, could be catastrophic if a close encounter occurred in the solar system. (Gravity from the wandering objects might disrupt orbits and/or fling bodies into other objects, thus resulting in meteorite impacts or climate change. Also, heat from the

wandering objects might cause extinctions; tidal forces could cause erosion along our coastlines.) Another threat might come from gamma ray bursts. Both are very unlikely.

Still others see extraterrestrial life as a possible threat to humankind; although alien life has never been found, scientists such as Carl Sagan have postulated that the existence of extraterrestrial life is very likely. In 1969, the "Extra-Terrestrial Exposure Law" was added to the Code of Federal Regulations (Title 14, Section 1211) in response to the possibility of biological contamination resulting from the US Apollo Space Program. It was removed in 1991. Scientists consider such a scenario technically possible, but unlikely.

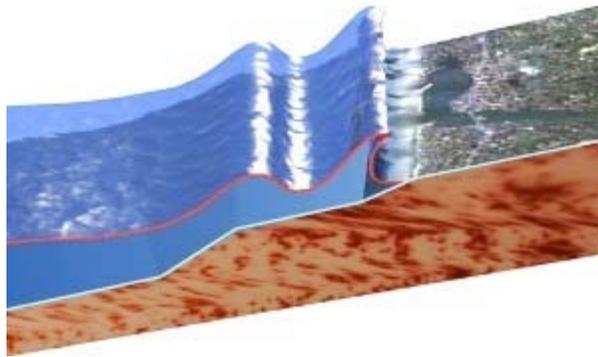
In April 2008, it was announced that two simulations of long-term planetary movement, one at Paris Observatory and the other at University of California, Santa Cruz indicate a 1% chance that Mercury's orbit could be made unstable by Jupiter's gravitational pull sometime during the lifespan of the sun. Were this to happen, the simulations suggest a collision with Earth could be one of four possible outcomes (the others being Mercury colliding with the Sun, colliding with Venus, or being ejected from the solar system altogether). If Mercury were to collide with the Earth, all life on Earth would be obliterated and the impact may displace enough matter into orbit to form another moon. Note that an asteroid just 15 km wide is said to have destroyed the dinosaurs; Mercury is some 5,000 km in diameter.

Earth

Global pandemic

A less predictable scenario is a global pandemic. For example, if HIV were to mutate and become as transmissible as the common cold, the consequences would be disastrous. It has been hypothesised that such an extremely virulent pathogen might not evolve. This is because a pathogen that quickly kills its hosts might not have enough time to spread to new ones, while one that kills its hosts more slowly or not at all will allow carriers more time to spread the infection, and thus likely out-compete a more lethal species or strain. This simple model predicts that if virulence and transmission are not linked in any way, pathogens will evolve towards low virulence and rapid transmission. However, this assumption is not always valid and in more complex models, where the level of virulence and the rate of transmission are related, high levels of virulence can evolve. The level of virulence that is possible is instead limited by the existence of complex populations of hosts, with different susceptibilities to infection, or by some hosts being geographically-isolated. The size of the host population and competition between different strains of pathogens can also alter virulence. Interestingly, a pathogen that only infects humans as a secondary host and usually infects another species (a zoonosis) may have little constraint on its virulence in people, since infection here is an accidental event and its evolution is driven by events in another species.

Megatsunami



An artist's rendering of wave shoaling of a tsunami

Megatsunami is an informal term to describe a tsunami that has initial wave heights that are much larger than normal tsunamis. Unlike usual tsunamis, which originate from tectonic activity and the raising or lowering of the sea floor, known megatsunamis have originated from large scale landslides or impact events.

Concept

A megatsunami is meant to refer to a tsunami with an initial wave amplitude (wave height) measured in several tens, hundreds, or possibly thousands of meters.

Normal tsunamis generated at sea have a small wave height offshore, and a very long wavelength (often hundreds of kilometers long). They generally pass unnoticed at sea, forming only a slight swell usually of the order of 30 cm (12 in) above the normal sea surface. When they reach land the wave height increases dramatically as the base of the wave pushes the water column above it upwards.

Megatsunamis can be caused by giant landslides and asteroid impacts. Underwater earthquakes or volcanic eruptions do not normally generate such large tsunamis, but landslides next to bodies of water resulting from earthquakes do, since they cause a massive amount of displacement.

History of the hypothesis

Geologists searching for oil in Alaska in 1953 observed that in Lituya Bay, mature tree growth did not extend to the shoreline as it did in many other bays in the region. Rather, there was a band of younger trees closer to the shore. Forestry workers, glaciologists, and geographers call the boundary between these bands a trim line. Trees just above the trim line showed severe scarring on their seaward side, whilst those from below the trim line did not. The scientists hypothesized that there had been an unusually large wave or waves

in the deep inlet. Because this is a recently deglaciated fjord with steep slopes and crossed by a major fault, one possibility was a landslide-generated tsunami.

On 9 July 1958, an earthquake of magnitude 7.7 (on the Richter scale), caused 90 million tonnes of rock and ice to drop into the deep water at the head of Lituya Bay. The block fell almost vertically and hit the water with sufficient force to create a wave approximately 524 meters high (1,724 feet). Howard Ulrich and his son, Howard Jr. were in the bay in their fishing boat when they saw the wave. They both survived and reported that the wave carried their boat "over the trees" on one of the initial waves which washed them back into the bay, though the larger wave did not harm them a great lot. A similar tsunami out at sea could come tens of kilometers inland.

This event and evidence of a potentially similar past event at the same location inspired the term *megatsunami*.

List of megatsunamis

Prehistoric

- The asteroid which created the Chicxulub crater in Yucatan approximately 65 million years BP would have generated some of the largest megatsunamis in Earth's history.
- A series of megatsunamis was generated by the bolide impact that created the Chesapeake Bay impact crater, about 35.5 million years BP.
- At Seton Portage, British Columbia, Canada, a freshwater megatsunami may have occurred approximately 10,000 BP. A huge block of the Cayoosh Range suddenly slid northwards into what had been a large lake spanning the area from Lillooet, British Columbia to near Birken, in the Gates Valley or Pemberton Pass to the southwest. The event has not been studied in detail, but the proto-lake (freshwater fjord) may have been at least as deep as the two present-day halves, Seton and Anderson Lakes, on either side of the Portage, suggesting that the surge generated by the giant landslide in the narrow mountain confines of the fjord valley may have been comparable in scale to Lituya Bay. Another more recent landslide on the south shore of Anderson Lake dropped a large portion of high mountainside down a debris chute, creating a rockwall "fan" which *must* have made a megatsunami-type wave, though not as large as the main one at the Portage.
- Approximately 8,000 BC, a massive volcanic landslide off of Mt. Etna, Sicily caused a megatsunami which devastated the eastern Mediterranean coastline on three continents.
- In the Norwegian Sea, the Storegga Slide caused a megatsunami approximately 7,000 years BP.

- Approximately 4,000 BP, a landslide on Réunion island, to the east of Madagascar, may have caused a megatsunami.
- The recently discovered undersea Burckle Crater located at the bottom of the Indian Ocean would have caused a megatsunami at the time of impact estimated to be c. 3,000–2,800 BC.
- Evidence for large landslides has been found in the form of extensive underwater debris aprons around many volcanic ocean islands which are composed of the material which has slid into the ocean. The island of Molokai had a catastrophic collapse over a million years ago; this underwater landslide likely caused large tsunamis. In recent years, five such debris aprons have been located around the Hawaiian Islands. The Canary Islands have at least 14 such debris aprons associated with the archipelago.

Modern

1792: Mount Unzen, Japan

In 1792, Mount Unzen in Japan erupted, causing part of the volcano to collapse into the sea. The landslide caused a megatsunami that reached 330 ft (100 metres) high and killed 15,000 people in the local fishing villages.

1958: Lituya Bay, Alaska, USA



Damage from the 1958 Lituya Bay megatsunami can be seen in this oblique aerial photograph of Lituya Bay, Alaska as the lighter areas at the shore where trees have been stripped away.

On 9 July 1958, a giant landslide at the head of Lituya Bay in Alaska, caused by an earthquake, generated a wave with an initial amplitude of 524 meters (1,720 ft). This is the highest wave ever recorded, and surged over the headland opposite, stripping trees and soil down to bedrock, and surged along the fjord which forms Lituya Bay, destroying a fishing boat anchored there and killing two people. Howard Ulrich and his son managed to ride the wave in their boat, and both survived.

1963: Vajont Dam, Italy

On 9 October 1963, a landslide above Vajont Dam in Italy produced a 250 m (820 ft) surge that overtopped the dam and destroyed the villages of Longarone, Pirago, Rivalta, Villanova and Faè, killing nearly 2,000 people.

1980: Spirit Lake, Washington, USA

On May 18, 1980, the upper 460 meters of Mount St. Helens failed and detached in a massive landslide. This released the pressure on the magma trapped beneath the summit bulge which exploded as a lateral blast, which then released the over-pressure on the magma chamber and resulted in a plinian eruption.

One lobe of the avalanche surged onto Spirit Lake, causing a megatsunami which pushed the lake waters in a series of surges, which reached a maximum height of 260 metres above the pre-eruption water level (~975 m asl). Above the upper limit of the tsunami, trees lie where they were knocked down by the pyroclastic surge; below the limit, the felled trees and the surge deposits were removed by the megatsunami and deposited in Spirit Lake.

Potential future megatsunamis

Experts interviewed by the BBC think that a massive landslide on a volcanic ocean island is the most likely future cause of a megatsunami. The size and power of a wave generated by such means could produce devastating effects, travelling across oceans and inundating up to 25 kilometres (16 mi) inland from the coast.

British Columbia

Some geologists consider that an unstable rock face at Mount Breakenridge above the north end of the giant fresh-water fjord of Harrison Lake in the Fraser Valley of southwestern British Columbia, Canada, could collapse into the lake, generating a megatsunami that might destroy the town of Harrison Hot Springs (located at its south end).

Canary Islands

Geologists S. Day and S. Ward consider that a megatsunami could be generated during a future eruption involving the Cumbre Vieja on the volcanic ocean island of La Palma, in the Canary Islands.

In 1949, the Cumbre Vieja volcano erupted at its Duraznero, Hoyo Negro and San Juan vents. During this eruption, an earthquake with an epicentre near the village of Jedy occurred. The following day Rubio Bonelli, a local geologist, visited the summit area and discovered that a fissure about 2.5 km long had opened on the eastern side of the summit. As a result, the western half of the Cumbre Vieja (which is the volcanically active arm of a triple-armed rift) had slipped about 2 m downwards and 1 m westwards towards the Atlantic Ocean.

The Cumbre Vieja volcano is currently in a dormant stage, but will almost certainly erupt again in the future. Day and Ward hypothesize that if such an eruption causes the western flank to fail, a megatsunami will be generated.

La Palma is currently the most volcanically active island in the Canary Islands Archipelago. It is likely that several eruptions would be required before failure would occur on Cumbre Vieja. However, the western half of the volcano has an approximate volume of 500 km^3 ($5 \times 10^{11} \text{ m}^3$) and an estimated mass of $1.5 \times 10^{15} \text{ kg}$. If it were to catastrophically slide into the ocean, it could generate a wave with an initial height of about 1,000 metres (3,281 ft) at the island, and a likely height of around 50 metres (164 ft) at the Caribbean and the Eastern North American seaboard when it runs ashore eight or more hours later. The likelihood of this happening is a matter of vigorous debate.

The last Cumbre Vieja eruption occurred in 1971 at the southern end of the sub-aerial section without any movement. The section affected by the 1949 eruption is currently stationary and does not appear to have moved since the initial rupture.

Geologists and volcanologists also disagree about whether an eruption on the Cumbre Vieja would cause a single large gravitational landslide or a series of smaller landslides.

Hawaii

Prehistoric sedimentary deposits on the Kohala Volcano, Lanai and Molokai controversially indicates that landslides from the flank of the Kilauea and Mauna Loa volcanoes in Hawaii may have triggered past megatsunamis, most recently at 120,000 BP. A future tsunami event is also possible, with the tsunami potentially reaching up to about a kilometer in height.

Climate change and global warming

Climate change is any long-term significant change in the expected patterns of average weather of a specific region (or, more relevantly to contemporary socio-political concerns, of the Earth as a whole) over an appropriately significant period of time. Climate change reflects abnormal variations to the expected climate within the Earth's atmosphere and subsequent effects on other parts of the Earth, such as in the ice caps over durations ranging from decades to millions of years. According to the UN's Office for the Coordination of Humanitarian Affairs (OCHA), climate disasters are on the rise. Around 70 percent of disasters are now climate related – up from around 50 percent from two decades ago. These disasters take a heavier human toll and come with a higher price tag. In the last decade, 2.4 billion people were affected by climate related disasters, compared to 1.7 billion in the previous decade and the cost of responding to disasters has risen tenfold between 1992 and 2008. Destructive sudden heavy rains, intense tropical storms, repeated flooding and droughts are likely to increase, as will the vulnerability of local communities in the absence of strong concerted action. Sea level rise may completely inundate certain areas.

Ice age

In the history of the Earth, twelve ice ages have occurred. More ice ages will be possible at an interval of 40,000–100,000 years. This would have a serious impact on civilization,

because vast areas of land (mainly in North America, Europe, and Asia) could become uninhabitable. It would still be possible to live in the tropical regions, but with possible loss of humidity/water. Currently, the world is existing in an interglacial period within a much older glacial event. The last glacial expansion ended about 10,000 years ago, and all civilizations evolved later.

Ecological disaster

An ecological disaster, such as world crop failure and collapse of ecosystem services, could be induced by the present trends of overpopulation, economic development, and non-sustainable agriculture. Most of these scenarios involve one or more of the following: Holocene extinction event, scarcity of water that could lead to approximately one half of the Earth's population being without safe drinking water, pollinator decline, overfishing, massive deforestation, desertification, climate change, or massive water pollution episodes. A very recent threat in this direction is colony collapse disorder, a phenomenon that might foreshadow the imminent extinction of the Western honeybee. As the bee plays a vital role in pollination, its extinction would severely disrupt the food chain.

World population and agricultural crisis

The 20th century saw a rapid increase in human population due to medical advances and massive increase in agricultural productivity made by the Green Revolution. Between 1950 and 1984, as the Green Revolution transformed agriculture around the globe, world grain production increased by 250%. The Green Revolution in agriculture helped food production to keep pace with worldwide population growth or actually enabled population growth. The energy for the Green Revolution was provided by fossil fuels in the form of fertilizers (natural gas), pesticides (oil), and hydrocarbon fueled irrigation. David Pimentel, professor of ecology and agriculture at Cornell University, and Mario Giampietro, senior researcher at the National Research Institute on Food and Nutrition (INRAN), place in their study *Food, Land, Population and the U.S. Economy* the maximum U.S. population for a sustainable economy at 200 million. To achieve a sustainable economy and avert disaster, the United States must reduce its population by at least one-third, and world population will have to be reduced by two-thirds, says the study.

The authors of this study believe that the mentioned agricultural crisis will only begin to impact us after 2020, and will not become critical until 2050. Geologist Dale Allen Pfeiffer claims that coming decades could see spiraling food prices without relief and massive starvation on a global level such as never experienced before.

Supervolcano

A **supervolcano** is a volcano capable of producing a volcanic eruption with ejecta greater than 1,000 cubic kilometers (240 cubic miles). This is thousands of times larger than most historic volcanic eruptions. Supervolcanoes can occur when magma in the Earth

rises into the crust from a hotspot but is unable to break through the crust. Pressure builds in a large and growing magma pool until the crust is unable to contain the pressure. They can also form at convergent plate boundaries (for example, Toba) and continental hotspot locations (for example, Yellowstone).

The Discovery Channel highlighted six known supervolcanoes: the Yellowstone, Long Valley, and Valles Caldera in the United States; Lake Toba, North Sumatra, Indonesia; Taupo Volcano, North Island, New Zealand; and Aira Caldera, Kagoshima Prefecture, Kyūshū, Japan. Although there are only a handful of Quaternary supervolcanoes, supervolcanic eruptions typically cover huge areas with lava and volcanic ash and cause a long-lasting change to weather (such as the triggering of a small ice age) sufficient to threaten the extinction of species.

Terminology

The term "supervolcano" was originally used in the BBC popular science television program *Horizon* in 2000 to refer to these types of eruptions. That program introduced the subject of large-scale volcanic eruptions to the general public.

Volcanologists and geologists do not refer to "supervolcanoes" in their scientific work, since this is a blanket term that can be applied to number of different geothermal conditions. Since 2003, however, the term has been used by professionals when presenting to the public. The term *megacaldera* is sometimes used for calderas with supervolcano characteristics, such as the Blake River Megacaldera Complex in the Abitibi greenstone belt of Ontario and Quebec, Canada. Eruptions that rate VEI 8 are termed "super eruptions".

Though there is no well-defined minimum explosive size for a "supervolcano", there are at least two types of volcanic eruption that have been identified as supervolcanoes: large igneous provinces and massive eruptions.

Large igneous provinces

Large igneous provinces (LIP) such as Iceland, the Siberian Traps, Deccan Traps, and the Ontong Java Plateau are extensive regions of basalts on a continental scale resulting from flood basalt eruptions. When created, these regions often occupy several thousand square kilometres and have volumes on the order of millions of cubic kilometers. In most cases, the lavas are normally laid down over several million years. They do release massive amounts of gases. The Réunion hotspot produced the Deccan Traps about 65 million years ago, coincident with the extinction of the dinosaurs at the end of the Cretaceous. Because the largest flood basalt event (the Siberian Traps) occurred around 250 Ma and was coincident with the largest mass extinction in history (end Permian), and the second largest flood basalt event (The Deccan Traps) occurred around 65 Ma and was coincident with the second largest extinction event (end Cretaceous), research continues into the effect of these volcanic outpourings and whether they contributed to mass extinctions.

Such outpourings are not explosive though fire fountains may occur. Many volcanologists consider that Iceland may be a LIP that is currently being formed. The last major outpouring occurred in 1783–84 from the Laki fissure which is ~40 km long. An estimated 14 km^3 of basaltic lava was poured out during the eruption.

The Ontong Java Plateau now has an area of about 2 million km^2 , and the province was at least 50% larger before the Manihiki and Hikurangi Plateaus broke away.

Massive explosive eruptions

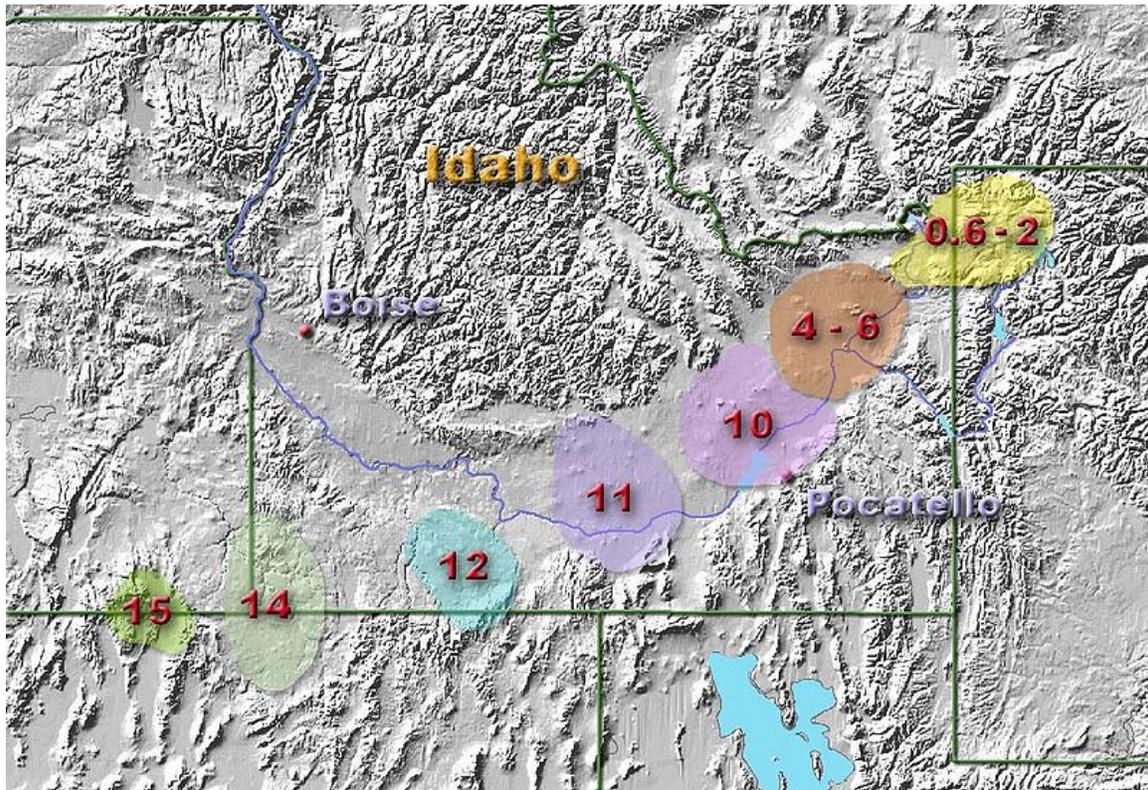
Eruptions with a Volcanic Explosivity Index of 8 (VEI-8) are colossal events that throw out at least $1,000 \text{ km}^3$ Dense Rock Equivalent (DRE) of ejecta; VEI-7 events eject at least 100 km^3 (DRE).

VEI-7 or 8 eruptions are so powerful that they often form circular calderas rather than cones because the downward withdrawal of magma causes the overlying mass to collapse and fill the void magma chamber beneath.

One of the classic calderas is at Glen Coe in the Grampian Mountains of Scotland. First described by Clough et al. (1909) its geology and volcanic succession has recently been re-analysed in the light of new discoveries. There is an accompanying 1:25000 solid geology map.

By way of comparison, the 1980 Mount St. Helens eruption was at the lower end of VEI-5 with 1.2 km^3 , and both Mount Pinatubo in 1991 and Krakatoa in 1883 were VEI-6 with 25 km^3 .

Known super eruptions



Location of Yellowstone Hotspot in Millions of Years Ago

Estimates of the volume of ejected material are given in parentheses.

VEI 8

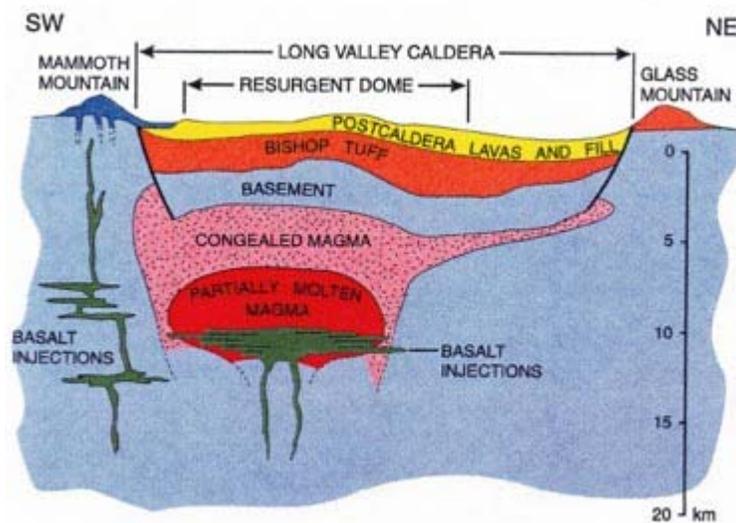
VEI 8 eruptions have happened in the following locations.

- Lake Taupo, Taupo Volcanic Zone, North Island, New Zealand—Oruanui eruption ~26,500 years ago (~1,170 km³)
- Lake Toba, Sumatra, Indonesia—~74,000 years ago (~2,800 km³)
- Whakamaru, Taupo Volcanic Zone, North Island, New Zealand—Whakamaru Ignimbrite/Mount Curl Tephra ~254,000 years ago (1,200-2,000 km³)
- Yellowstone Caldera, Lava Creek Tuff, Wyoming, United States, Yellowstone hotspot—640,000 years ago (1,000 km³)
- Island Park Caldera, Huckleberry Ridge Tuff, Idaho/Wyoming, United States, Yellowstone hotspot—2.1 million years ago (2,500 km³)
- Cerro Galan, Catamarca Province, Argentina—2.5 million years ago (1,050 km³)
- Atana Ignimbrite, Pacana Caldera, northern Chile—4 million years ago (2,500 km³)
- Heise volcanic field, Kilgore Tuff, Idaho, United States, Yellowstone hotspot—4.5 million years ago (1,800 km³).

- Heise volcanic field, Blacktail Tuff, Idaho, United States, Yellowstone hotspot—6.6 million years ago (1,500 km³).
- La Garita Caldera, Colorado, United States—Source of the enormous eruption of the Fish Canyon Tuff ~27.8 million years ago (~5,000 km³)

The Lake Toba eruption plunged the Earth into a volcanic winter, eradicating an estimated 60% of the human population (although humans managed to survive, even in the vicinity of the volcano). However the coincidental agreement in above sources about percentage value of extinction is contrary to differing estimates of human population size at that time.

VEI 7



Cross-section through Long Valley Caldera

VEI-7 volcanic events, less colossal but still supermassive, have occurred in the geological past. The only ones in historic times are Tambora, in 1815, Lake Taupo (Hatepe), around 180 CE, and possibly Baekdu Mountain, 969 CE (± 20 years).

- Tambora, Sumbawa Island, West Nusa Tenggara, Indonesia—1815 (160 km³), the following year 1816 became known as the "Year Without a Summer"
- Baekdu Mountain, China/North Korea—~969 CE (96 \pm 19 km³)
- Lake Taupo, Taupo Volcanic Zone, North Island, New Zealand—Hatepe eruption ~181 CE (120 km³)
- Kikai Caldera, Ryukyu Islands, Japan—~6,300 years ago (~4,300 BCE) (150 km³)
- Macauley Island, Kermadec Islands, New Zealand—~6,300 years ago (~4,300 BCE) (100 km³)
- Aira Caldera, Kyūshū, Japan—22,000 years ago (~110 km³)

- Rotoiti Ignimbrite, Taupo Volcanic Zone, North Island, New Zealand—~50,000 years ago (~240 km³)
- Campi Flegrei, Naples, Italy—39,280 ± 110 years ago (500 km³)
- Aso, Kyūshū, Japan—four large explosive eruptions between 300,000 to 80,000 years ago (last one >600 km³)
- Mamaku Ignimbrite, Rotorua Caldera, Taupo Volcanic Zone, North Island, New Zealand—240,000 years ago (>280 km³)
- Matahina Ignimbrite, Haroharo Caldera, Taupo Volcanic Zone, North Island, New Zealand—280,000 years ago (~120 km³)
- Long Valley Caldera, Bishop Tuff, California, United States—~760,000 years ago (600 km³)
- Valles Caldera, New Mexico, United States—~1.15 million years ago (~600 km³)
- Mangakino, Taupo Volcanic Zone, North Island, New Zealand—three eruptions from 0.97 to 1.23 million years ago (each > 300 km³)
- Henry's Fork Caldera, Mesa Falls Tuff, Idaho, United States, Yellowstone hotspot—1.3 million years ago (280 km³)
- Pastos Grandes Ignimbrite, Pastos Grandes Caldera, 2.9 million years ago (>820 km³)
- Heise volcanic field, Walcott Tuff, Idaho, United States, Yellowstone hotspot—6.4 million years ago (750 km³).
- Bruneau-Jarbidge, Idaho, United States, Yellowstone hotspot—~10–12 million years ago (>250 km³) (responsible for the Ashfall Fossil Beds ~1,600 km to the east)
- Bennett Lake Volcanic Complex, British Columbia/Yukon, Canada—~50 million years ago (850 km³)

Media portrayal



Satellite image of Lake Toba, the site of a VEI-8 eruption ~75,000 years ago



Volcano, lake, and caldera locations in the Taupo Volcanic Zone

- A National Geographic Channel documentary called *Earth Shocks* portrayed the destructive impact of the rapid eruption at Lake Toba approximately 75,000 years ago, which is thought to have caused a phenomenon known as the Millennial Ice Age that lasted for about 1,000 years and killed an estimated 60–75% of the human population of the time. But according to Alan Robock *et al.*, the Toba incident did not initiate an ice age, but rather exacerbated an ice age that had already been underway. Nevertheless, the climate recovered over a few decades.
- In 2005, an eruption of the Yellowstone supervolcano is one of the scenarios depicted in the docudrama *End Day*.

- In 2005, a two-part television docudrama called *Supervolcano* aired on BBC One, the Discovery Channel, and other television networks worldwide. It looked at the events that could take place if the Yellowstone supervolcano erupted. It featured footage of volcano eruptions from around the world and computer-generated imagery depicting the event. According to the program, such an eruption would have devastating effect across the globe and would cover virtually all of the United States with at least 1 cm of volcanic ash, causing mass destruction in the nearby vicinity and killing plants and wildlife across the continent. The dramatic elements in the program were followed by *Supervolcano: The Truth About Yellowstone*, a documentary about the evidence behind the film. The program had originally been scheduled to be transmitted in early 2005, but it was felt that this would be insensitive so soon after the 2004 Indian Ocean tsunami. The program and its accompanying documentaries were released on DVD region 2 simultaneously with its broadcast.
- *Nova* featured an episode "Mystery of the Megavolcano" in September 2006 examining such eruptions in the last 100,000 years.
- In 2006, the Sci Fi Channel aired the documentary *Countdown to Doomsday* which featured a segment called "Supervolcano". The same year, ABC News aired the documentary *Last Days on Earth*, which featured a segment called "Supervolcano". Also in 2006, the TV series *Stargate Atlantis* aired an episode called "Inferno" whose plot revolves around the discovery and subsequent eruption of a supervolcano on another planet.
- In 2008, the Yellowstone supervolcano was featured in the BBC program *10 Things You Didn't Know About Volcanoes*, presented by Dr. Iain Stewart, a volcanologist.
- In 2009, the Toba supervolcano was featured in the episode "Fire and Ice" of Animal Planet series *Animal Armageddon*.
- Also in 2009, the Yellowstone supervolcano erupts during the apocalyptic movie *2012*.

Warfare and mass destruction

The scenarios that have been explored most frequently are nuclear warfare and a Doomsday device. It is difficult to predict whether it would exterminate humanity, but very certainly could alter civilization in the event of a nuclear winter.

Artificial intelligence

Another category of disasters are unforeseen consequences of technology.

It has been suggested that learning computers that rapidly become superintelligent may take unforeseen actions or that robots would out-compete humanity. Because of its exceptional scheduling and organisational capability and the range of novel technologies it could develop, it is possible that the first Earth superintelligence to emerge could rapidly become very, very powerful. Quite possibly, it would be matchless and unrivaled: conceivably it would be able to bring about almost any possible outcome, and be able to foil virtually any attempt that threatened to prevent it achieving its desires. It could eliminate, wiping out if it chose, any other challenging rival intellects; alternatively it might manipulate or persuade them to change their behavior towards its own interests, or it may merely obstruct their attempts at interference.

Vernor Vinge has suggested that a moment may come when computers and robots are smarter than humans. He calls this "the Singularity." He suggests that it may be somewhat or possibly very dangerous for humans. This is discussed by a philosophy called Singularitarianism.

In 2009, experts attended a conference hosted by the Association for the Advancement of Artificial Intelligence (AAAI) to discuss whether computers and robots might be able to acquire any sort of autonomy, and how much these abilities might pose a threat or hazard. They noted that some robots have acquired various forms of semi-autonomy, including being able to find power sources on their own and being able to independently choose targets to attack with weapons. They also noted that some computer viruses can evade elimination and have achieved "cockroach intelligence." They noted that self-awareness as depicted in science-fiction is probably unlikely, but that there were other potential hazards and pitfalls. Various media sources and scientific groups have noted separate trends in differing areas which might together result in greater robotic functionalities and autonomy, and which pose some inherent concerns.

Some experts and academics have questioned the use of robots for military combat, especially when such robots are given some degree of autonomous functions. There are also concerns about technology which might allow some armed robots to be controlled mainly by other robots. The US Navy has funded a report which indicates that as military robots become more complex, there should be greater attention to implications of their ability to make autonomous decisions. One researcher states that autonomous robots might be more humane, as they could make decisions more effectively. However, other experts question this.

Biotechnology could lead to the creation of a pandemic, Nanotechnology could lead to grey goo in which out-of-control self-replicating robots consume all living matter on Earth while building more of themselves - in both cases, either deliberately or by accident. It has also been suggested that physical scientists might accidentally create a device that could destroy the earth and the solar system.

Climate change and ecology

It has been suggested that runaway global warming might cause the climate on Earth to become like Venus, which would make it uninhabitable. In less extreme scenarios it could cause the end of civilization, as we know it. According to a UN climate report, the Himalayan glaciers that are the sources of Asia's biggest rivers - Ganges, Indus, Brahmaputra, Yangtze, Mekong, Salween and Yellow - could disappear by 2350 as temperatures rise, although an initial announcement of that report erroneously stated the date as 2035. Approximately 3 billion people live in the drainage basin of the Himalayan rivers, which is almost half of the current human population (The Himalayan system, which includes outlying subranges, stretches across: Afghanistan, Bangladesh, Bhutan, People's Republic of China, India, Nepal, Burma, Cambodia, Thailand, Laos, Vietnam, Malaysia and Pakistan. Some of the world's major rivers, Ganges, Indus, Brahmaputra, Yangtze, Mekong, Salween and Yellow River, rise in the Himalayas, and their combined drainage basin in India, China, Pakistan, Bangladesh, Nepal and Myanmar could experience floods followed by droughts in coming decades. In India alone, the Ganges provides water for drinking and farming for more than 500 million people. The west coast of North America, which gets much of its water from glaciers in mountain ranges such as the Rocky Mountains, Cascade Mountains and Sierra Nevada, also would be affected. According to the California Department of Water Resources, if more water supplies are not found by 2020, California residents will face a water shortfall nearly as great as the amount consumed today. Directly linked to observed increases in the intensity and frequency of natural disasters, global warming and climate change are now considered key drivers behind rising global humanitarian and emergency relief needs. According to the UN's Office for the Coordination of Humanitarian Affairs (OCHA), climate disasters are on the rise. Around 70 percent of disasters are now climate related – up from around 50 percent from two decades ago. These disasters take a heavier human toll and come with a higher price tag. In the last decade, 2.4 billion people were affected by climate related disasters, compared to 1.7 billion in the previous decade and the cost of responding to disasters has risen tenfold between 1992 and 2008. Destructive sudden heavy rains, intense tropical storms, repeated flooding and droughts are likely to increase, as will the vulnerability of local communities in the absence of strong concerted action.

Approximately 40% of the world's agricultural land is seriously degraded. In Africa, if current trends of soil degradation continue, the continent might be able to feed just 25% of its population by 2025, according to UNU's Ghana-based Institute for Natural Resources in Africa.

James Lovelock, creator of the Gaia hypothesis, in his book *The Revenge of Gaia* (2006), has suggested that the elimination of rain forests, and the falling planetary biodiversity is removing the homeostatic negative feedback mechanisms that maintain climate stability by reducing the effects of greenhouse gas emissions (particularly carbon dioxide). With the heating of the oceans, the extension of the thermocline layer into Arctic and Antarctic waters is preventing the overturning and nutrient enrichment necessary for algal blooms of phytoplankton on which the ecosystems of these areas depend. With the loss of phytoplankton and tropical rain forests, two of the main carbon dioxide sinks for reducing

global warming, he suggests a runaway positive feedback effect could cause tropical deserts to cover most of the world's tropical regions, and the disappearance of polar ice caps, posing a serious challenge to global civilization.

Using scenario analysis, the Global Scenario Group (GSG), a coalition of international scientists convened by Paul Raskin, developed a series of possible futures for the world as it enters a Planetary Phase of Civilization. One scenario involves the complete breakdown of civilization as the effects of climate change become more pronounced, competition for scarce resources increases, and the rift between the poor and the wealthy widens. The GSG's other scenarios, such as Policy Reform, Eco-Communalism, and Great Transition avoid this societal collapse and eventually result in environmental and social sustainability. They claim the outcome is dependent on human choice and the possible formation of a global citizens movement which could influence the trajectory of global development.

Other scenarios

- **Peak oil:** Fossil Fuels attain a level of scarcity before an economically viable replacement is devised, leading firstly to economic strain, followed by the collapse of modern agriculture, then to mass-starvation.
- **Antibiotic resistance:** Natural selection would create super bacteria that are resistant to antibiotics, devastating the world population and causing a global collapse of civilization.
- **Gulf Stream shutdown:** There is some speculation that global warming could, via a shutdown or slowdown of the thermohaline circulation, trigger localized cooling in the North Atlantic and lead to cooling in that region. This would affect in particular areas like Ireland, the Nordic countries, and Britain that are warmed by the North Atlantic drift.
- **Mutual assured destruction:** A full scale nuclear war could kill billions, and the resulting nuclear winter would effectively crush any form of civilization.
- **Overpopulation:** Some scenarios of simultaneous ecological (food & water production) and economical collapses with overpopulation are presumed to lead to a global civil war, where the remaining habitable areas are destroyed by competing humans (so called 'Mad Max'-scenario).
- **Famine:** As of late 2007, increased farming for use in biofuels, along with world oil prices spiking to more than \$140 per barrel, had pushed up the price of grain used to feed poultry and dairy cows and other cattle, causing higher prices of wheat (up 58%), soybean (up 32%), and maize (up 11%) over the year. Food riots have recently taken place in many countries across the world. An epidemic of stem rust on wheat caused by race Ug99 is currently spreading across Africa and into Asia and is causing major concern. Scientists say millions of people face starvation.
- **Experimental accident:** Investigations in nuclear and high energy physics, such as the Trinity test and more recently with the Large Hadron Collider, theoretical chain-reaction global disasters triggered by these unusual conditions were worried about by some but have not yet occurred.

- Dysgenics: Widespread occurrence of defective or disadvantageous human genes could cause a catastrophic decline in the quality of human life, or its total cessation.
- Hypercane
- Economic collapse
- Mass extinction
- Overconsumption

Historical fictional scenarios

Sir Isaac Newton (1642–1727) studied old texts and surmised that the end of the world would happen no earlier than 2060, although he was reluctant to put an exact date on it.

The belief that the Mayan civilization's Long Count calendar ends abruptly on December 21, 2012, is a misconception due to the Mayan practice of using only five places in Long Count Calendar inscriptions. On some monuments the Mayan calculated dates far into the past and future but there is no end of the world date. There will be a Piktun ending (a cycle of 13 144,000 day Bak'tuns) on December 21, 2012. A Piktun marks the end of a 1,872,000 day or approximately 5125 year period and is a significant event in the Mayan calendar. However, there is no historical or scientific evidence that the Mayas believed it would be a doomsday. Some believe it will just be the beginning of another Piktun.

The cataclysmic pole shift hypothesis was formulated in 1872. Revisited repeatedly in the second half of the 20th century, it proposes that the axis of the Earth with respect to the crust could change extremely rapidly, causing massive earthquakes, tsunamis, and damaging local climate changes. The hypothesis is contradicted by the mainstream scientific interpretation of geological data, which indicates that true polar wander does occur, but very slowly over millions of years.

Chapter- 4

Asteroid Impact Avoidance



Artist's impression of a major impact event. The collision between Earth and an asteroid a few kilometres in diameter releases as much energy as the simultaneous detonation of several million nuclear bombs.

Asteroid mitigation strategies are "planetary defense" methods by which near-Earth objects could be diverted, preventing potentially catastrophic impact events. A sufficiently large impact would cause massive tsunamis and/or, by placing large quantities of dust into the stratosphere blocking sunlight, an impact winter. A collision between the earth and a ~10 km object 65 million years ago is believed to have produced the Chicxulub Crater and the Cretaceous–Tertiary extinction event.

While in theory the chances of such an event are no greater now than at any other time in history, recent astronomical events (such as Shoemaker-Levy 9) have drawn attention to such a threat, and advances in technology have opened up new options.

Detection efforts

What do we need to know?

Almost any deflection effort requires years of warning, allowing time to build a slow-pusher or explosive device to deflect the object.

An impact by a 10 km asteroid on the Earth is widely viewed as an extinction-level event, likely to cause catastrophic damage to the biosphere. Depending on speed, objects as small as 100 m in diameter are historically extremely destructive. There is also the threat from comets coming into the inner Solar System. The impact speed of a long-period comet would likely be several times greater than that of a near-Earth asteroid, making its impact much more destructive; in addition, the warning time is unlikely to be more than a few months.

Finding out the material composition of the object is also necessary before deciding which strategy is appropriate. Missions like the 2005 Deep Impact probe have provided valuable information on what to expect.

History of government mandates

In a 1992 report to NASA, a coordinated Spaceguard Survey was recommended to discover, verify and provide follow-up observations for Earth-crossing asteroids. This survey was expected to discover 90% of these objects larger than one kilometer within 25 years. Three years later, another NASA report recommended search surveys that would discover 60-70% of short-period, near-Earth objects larger than one kilometer within ten years and obtain 90% completeness within five more years.

In 1998, NASA formally embraced the goal of finding and cataloging, by 2008, 90% of all near-Earth objects (NEOs) with diameters of 1 km or larger than could represent a collision risk to Earth. The 1 km diameter metric was chosen after considerable study indicated that an impact of an object smaller than 1 km could cause significant local or regional damage but is unlikely to cause a worldwide catastrophe. The impact of an object much larger than 1 km diameter could well result in worldwide damage up to, and potentially including, extinction of the human race. The NASA commitment has resulted in the funding of a number of NEO search efforts that are making considerable progress toward the 90% goal by 2008.

NASA is close to achieving this goal, and should achieve it within a few years. However, as the 2009 discovery of an NEO approximately 2 to 3 kilometers in diameter demonstrates, there are still large objects to be detected.

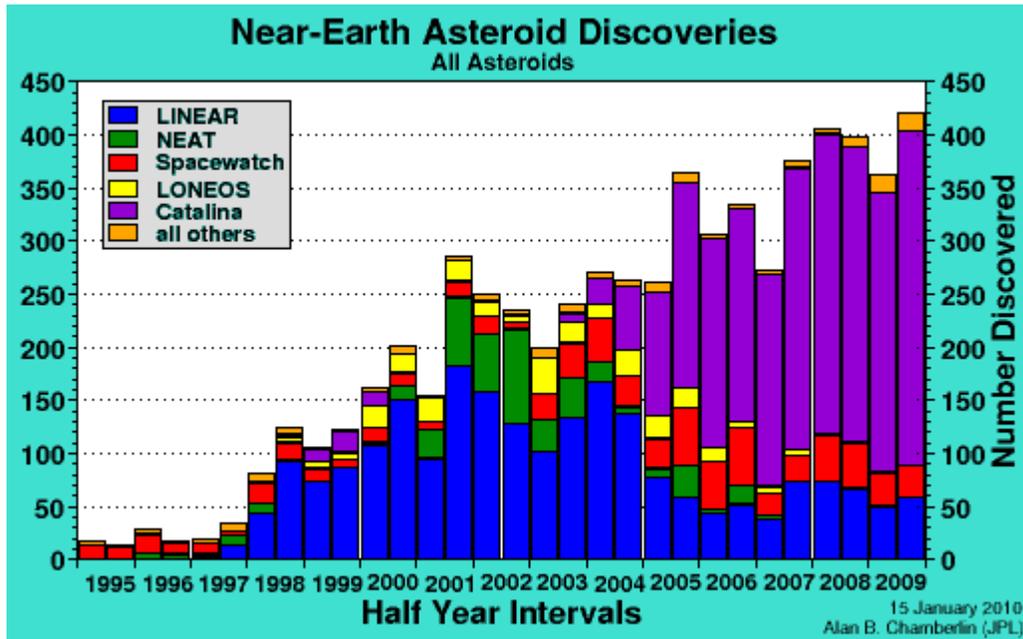
U.S. Representative George E. Brown, Jr. (D-CA) was quoted as voicing his support for planetary defense projects in *Air & Space Power Chronicles*, saying "If some day in the future we discover well in advance that an asteroid that is big enough to cause a mass extinction is going to hit the Earth, and then we alter the course of that asteroid so that it

does not hit us, it will be one of the most important accomplishments in all of human history."

Because of Congressman Brown's long-standing commitment to planetary defense, a U.S. House of Representatives' bill, H.R. 1022, was named in his honor: The George E. Brown, Jr. Near-Earth Object Survey Act. This bill "to provide for a Near-Earth Object Survey program to detect, track, catalogue, and characterize certain near-earth asteroids and comets" was introduced in March 2005 by Rep. Dana Rohrabacher (R-CA). It was eventually rolled into S.1281, the NASA Authorization Act of 2005, passed by Congress on December 22, 2005, subsequently signed by the President, and stating in part:

The U.S. Congress has declared that the general welfare and security of the United States require that the unique competence of NASA be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth. The NASA Administrator shall plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90% completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act. The NASA Administrator shall transmit to Congress not later than 1 year after the date of enactment of this Act an initial report that provides the following: (A) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions. (B) A recommended option and proposed budget to carry out the Survey program pursuant to the recommended option. (C) Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth. The result of this directive was a report presented to Congress in early March 2007. This was an Analysis of Alternatives (AoA) study led by NASA's Program Analysis and Evaluation (PA&E) office with support from outside consultants, the Aerospace Corporation, NASA Langley Research Center (LaRC), and SAIC (amongst others).

Ongoing projects



Number of NEOs detected by various projects

Astronomers have been conducting surveys to locate the NEOs, many (as of early 2007) funded by NASA's Near Earth Object (NEO) program office as part of their Spaceguard program. One of the best-known is LINEAR that began in 1996. By 2004 LINEAR was discovering tens of thousands of objects each year and accounting for 65% of all new asteroid detections. LINEAR uses two one-meter telescopes and one half-meter telescope based in New Mexico.

Spacewatch, which uses a 90 centimeter telescope sited at the Kitt Peak Observatory in Arizona, updated with automatic pointing, imaging, and analysis equipment to search the skies for intruders, was set up in 1980 by Tom Gehrels and Dr. Robert S. McMillan of the Lunar and Planetary Laboratory of the University of Arizona in Tucson, and is now being operated by Dr. McMillan. The Spacewatch project has acquired a 1.8 meter telescope, also at Kitt Peak, to hunt for NEOs, and has provided the old 90 centimeter telescope with an improved electronic imaging system with much greater resolution, improving its search capability.

Other near-earth object tracking programs include Near-Earth Asteroid Tracking (NEAT), Lowell Observatory Near-Earth-Object Search (LONEOS), Catalina Sky Survey, Campo Imperatore Near-Earth Objects Survey (CINEOS), Japanese Spaceguard Association, and Asiago-DLR Asteroid Survey. Pan-STARRS is expected to complete telescope construction by 2012.

"Spaceguard" is the name for these loosely affiliated programs, some of which receive NASA funding to meet a U.S. Congressional requirement to detect 90% of near-earth

asteroids over 1 km diameter by 2008. A 2003 NASA study of a follow-on program suggests spending US\$250–450 million to detect 90% of all near-earth asteroids 140 meters and larger by 2028.

Orbit@home provides distributed computing resources to optimize search strategy, and NEODyS is an online database of known NEOs.

Detection from space

On November 8, 2007, the House Committee on Science and Technology's Subcommittee on Space and Aeronautics held a hearing to examine the status of NASA's Near-Earth Object survey program. The prospect of using the Wide-field Infrared Survey Explorer was proposed by NASA officials.

WISE will survey the sky in the infrared band at a very high sensitivity. Asteroids that absorb solar radiation can be observed through the infrared band. NASA officials told Committee staff that NASA plans to use WISE to detect NEOs, in addition to performing its science goals. It is projected that WISE could detect 400 NEOs (roughly two percent of the estimated NEO population of interest) within the one-year mission.

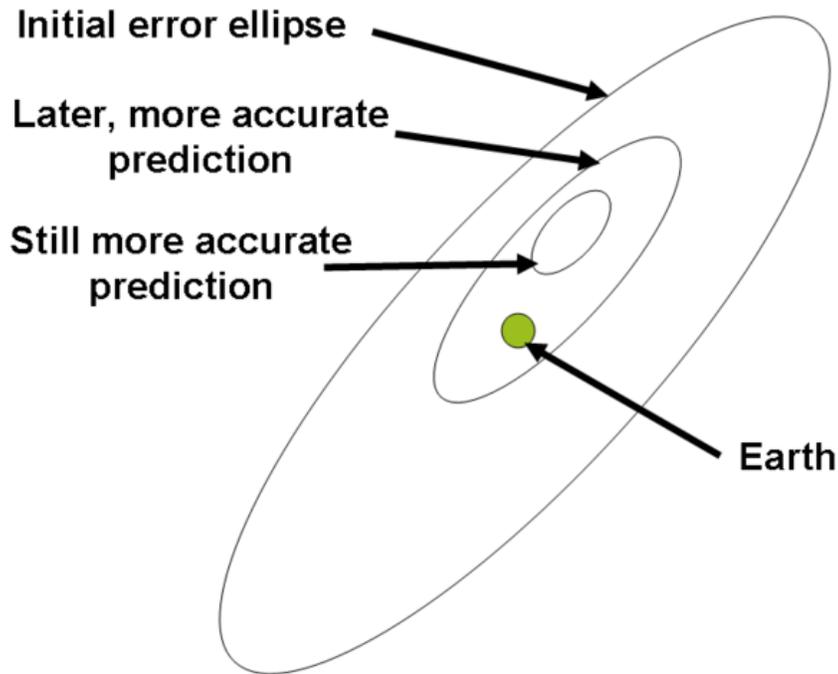
NEOSSat is a micro satellite by Canada's CSA that will hunt for NEOs from space.

Results

Research published in the March 26, 2009 issue of the journal *Nature*, describes how scientists were able to identify an asteroid in space before it entered Earth's atmosphere, enabling computers to determine its area of origin in the solar system as well as predict the arrival time and location on Earth of its shattered surviving parts. The four-meter-diameter asteroid, called 2008 TC₃, was initially sighted by the automated Catalina Sky Survey telescope, on October 6, 2008. Computations correctly predicted impact would occur 19 hours after discovery in the Nubian Desert of northern Sudan.

A number of potential threats have been identified, such as 99942 Apophis (previously known by its provisional designation 2004 MN₄), which had been given an impact probability of ~3% for the year 2029. This probability has been revised to zero on the basis of new observations.

Impact probability calculation pattern



Why asteroid impact probability goes up, then down

The ellipses in the diagram at right show the likely asteroid position at closest earth approach. At first, with only a few asteroid observations, the error ellipse is very large and includes the Earth. Further observations shrink the error ellipse, but it still includes the Earth. This raises the impact probability, since the Earth now covers a larger fraction of the error region. Finally, yet more observations (often radar observations, or discovery of a previous sighting of the same asteroid on archival images) shrink the ellipse until the Earth is outside the error region, and the impact probability returns to near zero.

Collision avoidance strategies

Various collision avoidance techniques have different trade-offs with respect to metrics such as overall performance, cost, operations, and technology readiness. There are various methods for changing the course of an asteroid/comet. These can be differentiated by various types of attributes such as the type of mitigation (deflection or fragmentation), energy source (kinetic, electromagnetic, gravitational, solar/thermal, or nuclear), and approach strategy (interception, rendezvous, or remote station). Strategies fall into two basic sets: destruction and delay.

Destruction concentrates on rendering the impactor harmless by fragmenting it and scattering the fragments so that they miss the Earth or burn up in the atmosphere. This does not always solve the problem, as sufficient amounts of material hitting the Earth at high speed can be devastating even if they are not collected together in a single body. The amount of energy released by a single large collision or many small collisions is essentially the same, given the physics of kinetic and potential energy. If a large amount of energy is transmitted, it could heat the surface of the planet to an uninhabitable temperature.

Collision avoidance strategies can also be seen as either direct, or indirect. The direct methods, such as nuclear devices or kinetic impactors, violently intercept the bolide's path. Direct methods are preferred because they are generally less costly in time and money. Their effects may be immediate, thus saving precious time. These methods might work for short-notice, or even long-notice threats, from solid objects that can be directly pushed, but probably not effective against loosely aggregated rubble piles. The indirect methods, such as gravity tractors, attaching rockets or mass drivers, laser canons, etc., will travel to the object then take more time to change course up to 180 degrees to fly along side, and then will also take much more time to change the asteroids path just enough so it will miss Earth.

Many NEOs are "flying rubble piles" only loosely held together by gravity, and a deflection attempt might just break up the object without sufficiently adjusting its course. If an asteroid breaks into fragments, any fragment larger than 35 m across would not burn up in the atmosphere and itself could impact Earth. Tracking the thousands of fragments that could result from such an explosion would be a very daunting task. Many small impacts could cause greater devastation than one large impact.

Against some rubble piles, a nuclear device may be delivered to it and dock with it, then it could penetrate to its center, and explode sending fragments in all directions, thus reducing the amount of material reaching the Earth. The explosion can also increase the surface area of the threat enough so that more pieces will burn up harmlessly high in the atmosphere.

Delay exploits the fact that both the Earth and the impactor are in orbit. An impact occurs when both reach the same point in space at the same time, or more correctly when some point on Earth's surface intersects the impactor's orbit when the impactor arrives. Since the Earth is approximately 12,750 km in diameter and moves at approx. 30 km per second in its orbit, it travels a distance of one planetary diameter in about 425 seconds, or slightly over seven minutes. Delaying, or advancing the impactor's arrival by times of this magnitude can, depending on the exact geometry of the impact, cause it to miss the Earth. By the same token, the arrival time of the impactor must be known to this accuracy in order to forecast the impact at all, and to determine how to affect its velocity.

Nuclear weapons

Detonating an explosive nuclear device above the surface (or on the surface or beneath it) of an NEO would be one option, with the blast vaporizing part of the surface of the object and nudging it off course with the reaction. This is a form of nuclear pulse propulsion. Even if not completely vaporized, the resulting reduction of mass from the blast combined with the radiation blast and rocket exhaust effect from ejecta could produce positive results.

Another proposed solution is to detonate a series of smaller nuclear devices alongside the asteroid, far enough away as not to fracture the object. Providing this was done far enough in advance, the relatively small forces from any number of nuclear blasts could be enough to alter the object's trajectory enough to avoid an impact. The 1964 book *Islands in Space*, calculates that a nuclear megatonnage necessary for several deflection scenarios exists. In 1967, graduate students under Professor Paul Sandorff at the Massachusetts Institute of Technology designed a system using rockets and nuclear explosions to prevent a hypothetical impact on Earth by the asteroid 1566 Icarus. This design study was later published as Project Icarus which served as the inspiration for the 1979 film *Meteor*.

Kinetic impact

The hurling of a massive object at the NEO, such as a spacecraft or another near-earth object, is another violent possibility. A small asteroid or large mass in a stable high-Earth orbit would have tremendous kinetic energy stored up. With the addition of some thrust from mounted rockets (plasma or otherwise), it could be used like a stone from a slingshot to deflect the incoming threat.

An alternative means of deflecting an asteroid is to attempt to directly alter its momentum by sending a spacecraft to collide with the asteroid.

The European Space Agency is already studying the preliminary design of a space mission able to demonstrate this futuristic technology. The mission, named Don Quijote, is the first real asteroid deflection mission ever designed.

In the case of 99942 Apophis it has been demonstrated by ESA's Advanced Concepts Team that deflection could be achieved by sending a simple spacecraft weighing less than one ton to impact against the asteroid. During a trade-off study one of the leading researchers argued that a strategy called 'kinetic impactor deflection' was more efficient than others.

Asteroid gravitational tractor

A **gravity tractor** (GT) is a spacecraft that deflects another object in space, typically a potentially hazardous asteroid that might impact Earth, without physically contacting it, using only its gravitational field to transmit the required impulse. The tractor spacecraft

could either hover near the object being deflected or orbit near it. The concept has the advantage that essentially nothing need be known about the mechanical composition and structure of the asteroid in advance.

Advantages

A number of considerations arise concerning means for avoiding a devastating collision with an asteroidal object, should one be discovered on a trajectory that were determined to lead to Earth impact at some future date. The one that has caused the greatest concern is how to transmit the impulse required (possibly quite large), to an asteroid of unknown mass, composition, and mechanical strength, without shattering it into fragments, some of which might be themselves dangerous to Earth if left in a collision orbit. The GT solves this problem by gently accelerating the object as a whole over an extended period of time, using the spacecraft's own mass and associated gravitational field to effect the necessary deflecting force. Because of the universality of gravitation, affecting as it does all mass alike, the asteroid would be accelerated almost uniformly as a whole, with only tidal forces (which should be extremely small) causing any stresses to its internal structure.

A further advantage is that a transponder on the spacecraft, by continuously monitoring the position and velocity of the tractor/asteroid system, could enable the post-deflection trajectory of the asteroid to be accurately known, ensuring its final placement into a safe orbit.

Limitations

The most important limitations of the tractor concept are that if the required impulse is large, it requires a correspondingly massive spacecraft, a large propulsion capability on the part of the tractor spacecraft, and a long period to effect the change. If the mass of the asteroidal body is M and the change in its velocity required is V , then the change in its momentum is p :

$$p = MV = Ft,$$

where F is the average force, applied over a time t . By the law of conservation of momentum, which is equivalent to Newton's Third Law of action and reaction, the spacecraft propulsion must provide the same total impulse. Also, in order that the spacecraft not simply be driven off to infinity by this propulsive force, it must be balanced, on the average, by the gravitational attraction of the asteroid for the spacecraft. Since the gravitational attraction is likely to be fairly small for a spacecraft of reasonable mass, the time t is likely to be rather long. This in turn entails that the spacecraft, necessarily massive already, must match velocity with the asteroid, further increasing the propulsive capability required, and then orbit or hover above it for an extended period. The high propulsion capability needed, together with the rather low thrust required, suggests an ion drive as the appropriate thruster. Stationkeeping or maintaining a stable orbit close to the asteroid would be complicated if the object has a complex shape or a

complex rotational behavior, as was the case for the NEAR mission that visited 433 Eros. If the asteroid were a binary system, which is now known to be fairly common, the situation would be yet more complex, though surely still manageable. Beacons attached to the asteroid communicating with the tractor spacecraft could track relative locations leading to stationkeeping adjustments of the spacecraft to maximize the gravitational force while minimizing spacecraft fuel requirements.

In any case, the tractor method appears most useful for objects of low to moderate mass, needing modest corrective impulse, and for which an extended period of time is available to effect the correction.

Another limitation for a hovering or stationkeeping gravity tractor is the exhaust configuration. With the most efficient hovering design (that is, pointing the exhaust directly at the target object for maximum force per unit of fuel), the expelled reaction mass hits the target head-on, imparting a force in the exact opposite direction to the gravitational pull of the tractor. It would therefore be necessary to use the orbiting-tractor scheme described below, or else design the hovering tractor so that its exhaust is directed at a slight angle away from the object, while still pointing “down” enough to keep a steady hover. This requires greater thrust and correspondingly increased fuel consumption for each m/s change in the target’s velocity.

Example

To get a feel for the magnitude of these issues, let us suppose that a NEO of size around 100 m, and mass of one million metric tons, threatened to impact Earth. Suppose also that

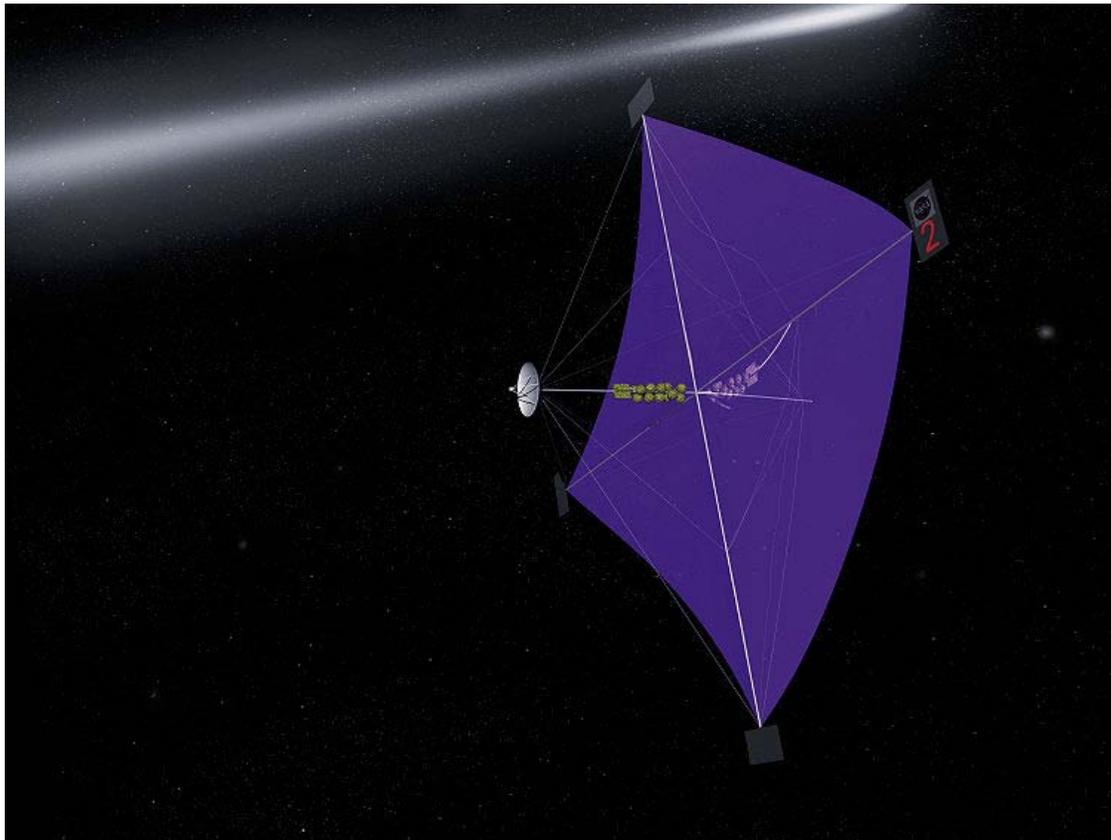
- a velocity correction of 1 cm/s would be adequate to place it in a safe and stable orbit, missing Earth
- that the correction needed to be applied within a period of 10 years.

With these parameters, the required impulse would be: $V \times M = 0.01 \text{ [m/s]} \times 10^9 \text{ [kg]} = 10^7 \text{ [N-s]}$, so that the average tractor force on the asteroid for 10 years, $= 3.156 \times 10^8 \text{ s}$, would need to be about 0.032 newtons. An ion-electric spacecraft with a specific impulse of 10,000 N-s per kg, corresponding to an ion beam velocity of 10 km/s (about twenty that obtained with the best chemical rockets), would require 1,000 kg of reaction mass (Xe is currently favored) to provide the impulse. The kinetic power of the ion beam would then be approximately 317 W; the input electric power to the power converter and ion drive would of course be substantially higher. The spacecraft would need to have enough mass and remain sufficiently close to the asteroid that the component of the average gravitational force on the asteroid in the desired direction would equal or exceed the required 0.032 N. Assuming the spacecraft is hovering the asteroid at a distance of 200m to its centre of mass, that would require it to have a mass of about 20 metric tonnes, because due to the gravitational force we have

$$m_2 = \frac{Fr^2}{Gm_1} = \frac{0.032[N] \times (200[m])^2}{6.674 \times 10^{-11}[Nm^2kg^{-2}] \times 10^9[kg]} \approx 19200kg$$

Considering possible hovering positions or orbits of the tractor around the asteroid, note that if two objects are gravitationally bound in a mutual orbit, then if one receives an arbitrary impulse which is less than that needed to free it from orbit around the other, because of the gravitational forces between them, the impulse will alter the momentum of both, together regarded as a composite system. That is, so long as the tractor remains in a bound orbit, any propulsive force applied to it will be effectively transferred to the asteroid it orbits. This permits a wide variety of orbits or hovering strategies for the tractor. One obvious possibility is for the spacecraft to orbit the NEO with the normal to the orbit in the direction of the desired force. The ion beam would then be directed in the opposite direction, also perpendicular to the orbit plane. This would result in the plane of the orbit being shifted somewhat away from the center of the asteroid, "towing" it, while the orbital velocity, normal to the thrust, remains constant. The orbital period would be a few hours, essentially independent of size, but weakly dependent on the density of the target body.

Use of focused solar energy



NASA study of a solar sail. The sail would be 0.5 km wide.

H. Jay Melosh proposed to deflect an asteroid or comet by focusing solar energy onto its surface to create thrust from the resulting vaporization of material, or to amplify the Yarkovsky effect. Over a span of months or years enough solar radiation can be directed onto the object to deflect it.

This method would first require the construction of a space station with a system of gigantic lens and magnifying glasses near earth. Then the station would be transported toward the Sun.

Mass driver



A mass driver for lunar launch (artist's conception)

A **mass driver** or **electromagnetic catapult** is a proposed method of non-rocket spacelaunch which would use a linear motor to accelerate and catapult payloads up to high speeds. All existing and contemplated mass drivers use coils of wire energized by electricity to make electromagnets. Sequential firing of a row of electromagnets accelerates the payload along a path. After leaving the path, the payload continues to move due to inertia.

A mass driver is essentially a coilgun that magnetically accelerates a package consisting of a magnetisable holder containing a payload. Once the payload has been accelerated, the two separate, and the holder is slowed and recycled for another payload.

Mass drivers can be used to propel spacecraft in two different ways: A large, ground-based mass driver could be used to launch spacecraft away from the Earth or another

planet. A spacecraft could have a mass driver on board, flinging large pieces of material into space to propel itself. A hybrid design is also possible.

Miniaturized mass drivers can also be used as weapons in a similar manner as classic firearms or cannon using chemical combustion.

Fixed mass drivers

Generally speaking, mass drivers are practical for small objects at a few kilometers per second; for example 1 kg at 2.5 km/s. Heavier objects go proportionally more slowly; and lighter objects may be projected at 20 km/s or more. The limits are generally the cost of the silicon to switch the current and the cost of the power supply and temporary energy storage for it. However, energy can be stored inductively in superconducting coils. A 1 km long mass driver made of superconducting coils can accelerate a 20 kg vehicle to 10.5 km/s at a conversion efficiency of 80%, and average acceleration of 5,600 g. Even so, Earth-based Mass drivers for propelling one-tonne vehicles to orbit are unlikely to be cost effective in the near future.

The Earth's strong gravity and thick atmosphere make such an installation difficult, so many proposals have been put forward to install mass drivers on the moon where the lower gravity and lack of atmosphere significantly reduce the required velocity to reach lunar orbit.

Most serious mass driver designs use superconducting coils to achieve reasonable energetic efficiency (approximately 50%). The best known performance occurs with an aluminum coil as the payload. The coils of the mass-driver induce eddy-currents in the payload's coil, and then act on the resulting magnetic field. There are two sections of a mass-driver. The maximum acceleration part spaces the coils at constant distances, and synchronize the coil currents to the bucket. In this section, the acceleration increases as the velocity increases, up to the maximum that the bucket can take. After that, the constant acceleration region begins. This region spaces the coils at increasing distances to give a fixed amount of velocity increase per unit of time.

In this mode, the major proposal for use of mass-drivers was to transport lunar surface material to space habitats so that it could be processed using solar energy. The Space Studies Institute showed that this application was reasonably practical.

In the prototypes, the payload would be held in a bucket and then released, so that the bucket can be decelerated and reused. A disposable bucket, on the other hand, would avail acceleration along the whole track.

On Earth

In contrast to a space gun, a mass driver can have a length of hundreds of kilometers and therefore achieve acceleration without excessive g forces to the passengers. It can be constructed as a very long and mainly horizontally aligned launch track for spacelaunch,

targeted upwards at the end, partly by bending of the track upwards and partly by Earth's curvature in the other direction.

Natural elevations, such as mountains, may facilitate the construction of the distant, upwardly targeted part. The higher up the track terminates, the less resistance from the atmosphere the launched object will receive.

By being mainly located slightly above, on or beneath the ground, a mass driver may be easier to maintain compared with many other structures of non-rocket spacelaunch. If not underground then it still needs to be housed in a pipe that is constantly vacuum pumped in order to reduce drag.

In order to be able to launch humans and delicate instruments, it would need to be several hundreds of kilometres long. For rugged objects, with magnetic assistance, a significantly smaller, circular, track may suffice.

A mass driver on Earth would be a compromise system. A mass driver would accelerate a payload up to some high speed which would not be high enough for orbit. It would then release the payload, which would complete the launch with rockets. This would drastically reduce the amount of velocity needed to be provided by rockets to reach orbit. On Earth, a mass driver design could possibly use well-tested maglev components.

Spacecraft-based mass drivers

A spacecraft could carry a mass driver as its primary engine. With a suitable source of electrical power (probably a nuclear reactor) the spaceship could then use the mass driver to accelerate pieces of matter of almost any sort, boosting itself in the opposite direction. At the smallest scale of reaction mass, this type of drive is called an ion drive.

No theoretical limit is known for the size, acceleration or muzzle energy of linear motors. However, at higher muzzle velocities, energetic efficiency is inevitably very poor. While linear motors can, with current technology, convert up to about 50% of the electrical energy into kinetic energy of the projectile, the energy of interest is the kinetic energy of the vehicle, and as the muzzle velocity increases, this is a smaller and smaller percentage of the generated power.

Since kinetic energy of the projectile is $\frac{1}{2}mv^2$, the energy requirements vary with the square of the specific impulse, so in a design one must choose a tradeoff between energy consumption and consumption of reaction mass. In addition, since momentum of a particle of mass m has momentum mv - proportional to velocity, but energy is a square law, so the average thrust for a given energy is inversely proportional to the velocity of the particles. In other words, heavier projectile masses give lower specific impulse but proportionately higher thrust.

Since a mass driver could use any type of mass for reaction mass to move the spacecraft, this, or some variation, seems ideal for deep-space vehicles that scavenge reaction mass from found resources.

One possible drawback of the mass driver is that it has the potential to send solid reaction mass travelling at dangerously high relative speeds into useful orbits and traffic lanes. To overcome this problem, most schemes plan to throw finely-divided dust. Alternately, liquid oxygen could be used as reaction mass, which upon release would boil down to its molecular state. Propelling the reaction mass to solar escape velocity is another way to ensure that it will not remain a hazard.

Space is almost completely empty, so propellant sources are only to be found at asteroids, comets, moons and planets.

Hybrid mass drivers

Another variation is to have a mass-driver on a spacecraft, and use it to "reflect" masses from a stationary mass-driver. Each deceleration and acceleration of the mass contributes to the momentum of the spacecraft. The spacecraft need not carry reaction mass, and doesn't even need much electricity, beyond the amount needed to replace losses in the electronics. The system could also be used to deliver pellets of fuel to the spacecraft for use in powering some other propulsion system. This could be considered a form of beam-powered propulsion.

Another theoretical use for this concept of propulsion can be found in space fountains, a system in which a continuous stream of pellets in a circular track holds up a tall (and heavy) structure.

Mass drivers as weapons

High-acceleration linear motors are currently undergoing active research by the military for use as (ground-based or ship-based) armor-piercing weapons. Since a mass driver is essentially a very large, very high-velocity linear motor, it could in principle be used as a very large weapon, either firing directly on a target in space, or used to attack a location on a planet's surface from a position in orbit, long range over-the-horizon indirect fire, or from a nearby planetary body, such as a moon.

Practical attempts

Prototype mass drivers have existed since 1976 (Mass Driver 1). Most were constructed by the US Space Studies Institute in order to prove their properties and practicality.

In fiction

Various types of devices resembling mass drivers have been a staple of science fiction for decades.

Conventional rocket motor

Attaching any spacecraft propulsion device would have a similar effect of giving a steady push, possibly forcing the asteroid onto a trajectory that takes it away from Earth. An in-space rocket engine that is capable of imparting an impulse of 10^6 N·s (E.g. adding 1 km/s to a 1000 kg vehicle), will have a relatively small effect on a relatively small asteroid that has a mass of roughly a million times more. Chapman, Durda, and Gold's white paper calculates deflections using existing chemical rockets delivered to the asteroid.

Other proposals

- Non-conventional engines, such as VASIMR
- Wrapping the asteroid in a sheet of reflective plastic such as aluminized PET film as a solar sail
- "Painting" or dusting the object with titanium dioxide (white) or soot (black) to alter its trajectory via the Yarkovsky effect.
- Planetary scientist Eugene Shoemaker in 1996 proposed deflecting a potential impactor by releasing a cloud of steam in the path of the object, hopefully gently slowing it. Nick Szabo in 1990 sketched a similar idea, "cometary aerobraking", the targeting of a comet or ice construct at an asteroid, then vaporizing the ice with nuclear explosives to form a temporary atmosphere in the path of the asteroid.
- Attaching a tether and ballast mass to the asteroid to alter its trajectory by changing its center of mass.
- Laser ablation
- Magnetic Flux Compression
- NEONet

Deflection technology concerns

Carl Sagan, in his book *Pale Blue Dot*, expressed concerns about deflection technology: that any method capable of deflecting impactors *away* from Earth could also be abused to divert non-threatening bodies *toward* the planet. Considering the history of genocidal political leaders and the possibility of the bureaucratic obscuring of any such project's true goals to most of its scientific participants, he judged the Earth at greater risk from a man-made impact than a natural one. Sagan instead suggested that deflection technology should only be developed in an actual emergency situation.

Analysis of the uncertainty involved in nuclear deflection shows that the ability to protect the planet does not imply the ability to target the planet. A nuclear bomb which changed an asteroid's velocity by 10 meters/second (plus or minus 20%) would be adequate to push it out of an earth-impacting orbit. However, if the uncertainty of the velocity change was more than a few percent, there would be no chance of directing the asteroid to a particular target.

According to Rusty Schweickart, the gravitational tractor method is also controversial because during the process of changing an asteroid's trajectory the point on Earth where it could most likely hit would be slowly shifted across different countries. It means that the threat for the entire planet would be minimized at the cost of some specific states' security. In Schweickart's opinion, choosing the way the asteroid should be "dragged" would be a tough diplomatic decision.

Planetary defense timeline

- In their 1964 book, *Islands in Space*, Dandridge M. Cole and Donald W. Cox noted the dangers of planetoid impacts, both those occurring naturally and those that might be brought about with hostile intent. They argued for cataloging the minor planets and developing the technologies to land on, deflect, or even capture planetoids.
- In the 1980s NASA studied evidence of past strikes on planet Earth, and the risk of this happening at our current level of civilization. This led to a program that maps which objects in our solar system both cross Earth's orbit and are large enough to cause serious damage if they ever hit.
- In the 1990s, US Congress held hearings to consider the risks and what needed to be done about them. This led to a US\$3 million annual budget for programs like Spaceguard and the near-earth object program, as managed by NASA and USAF.
- In 2005 the world's astronauts published an open letter through the Association of Space Explorers calling for a united push to develop strategies to protect Earth from the risk of a cosmic collision.
- It is currently (as of late 2007) believed that there are approximately 20,000 objects capable of crossing Earth's orbit and large enough (140 meters or larger) to warrant concern. On the average, one of these will collide with Earth each 5,000 years, unless preventative measures are undertaken. It is now anticipated that by year 2008, 90% of such objects that are 1 km or more in diameter will have been identified and will be monitored. The further task of identifying and monitoring all such objects of 140m or greater is expected to be complete around 2020.
- The Catalina Sky Survey (CSS) is one of NASA's four funded surveys to carry out a 1998 U.S. Congress mandate to find and catalog by the end of 2008, at least 90 percent of all near-Earth objects (NEOs) larger than 1 kilometer across. CSS discovered 310 NEOs in 2005, 400 in 2006 and the record will be broken with 450 NEOs found in 2007. In doing this survey they discovered on November 20, 2007, an asteroid, designated 2007 WD₅, which initially was estimated to have a chance of hitting Mars on January 30, 2008, but further observations during the

following weeks allowed NASA to rule out an impact. NASA estimated a near miss by 26,000 km.