21 November 2019

CULTURAL SELF-DESTRUCTION, NATURAL DISASTERS, & L

Homework #8 due Monday, 12/9 (after Thanksgiving break)

1

Cultural self-destruction, Natural disasters, & L

Self-imposed limitations on a civilization's lifespan:

- Uncommunicativeness
- Overpopulation and Malthusian collapse
- Resource depletion
- Destruction of habitat
  - Nuclear war and nuclear winter
  - CO2, ocean acidification, and catastrophic global warming

Mass extinctions in the last 600 Myr, presumed to be due to natural causes

Sudden climate change caused by

Supervolcanism

Impact by near-Earth asteroids

Instability due to unfortunate continental and orbital position

Gamma-ray bursts and other supernovae

2

Review question!

The main achievements of these two civilizations were invented independent of one another.

A. China and Egypt
B. Egypt and Sumer
C. Sumer and Mesoamerica
D. Mesoamerica and India
E. India and China

Shooting ourselves in the foot

Technological civilizations can collapse and/or lose the ability to communicate with those on other planets by two general means: self-inflicted damage and natural disasters. First, we will discuss the self-inflicted damage, of which there are four main types listed below in order of increasing danger.

1. Loss of interest in searching for other civilizations while retaining technological capability
2. Population growth to the point of societal collapse
3. Depletion of resources within reach of the civilization
4. Destruction of the habitability of the planet(s) on which the civilization resides

Being uncommunicative

Just because a civilization *can* communicate with others far away does not mean that it will. Best local analogy: China.

- China has been a leading civilization, capable of exploring far past its borders, continuously for about 3500 years.
- Yet, for almost all this time, it not only denied interest in other cultures but has been proud of that.
  - E.g. the Qing Dynasty's Qianlong Emperor, in refusing the British request to exchange ambassadors in 1793:

"This request is contrary to all usage of my dynasty… I set no value on objects strange or ingenious, and have no use for your country's manufactures."

5

Being uncommunicative

- In the early years of the Tang Dynasty (618-907 AD), the borders of China were advanced along the Silk Road as far as modern Kazakhstan, but China lost interest in further advancement after losing a battle (Talas River, 751 AD) to the Arabs of the Abbasid Caliphate, never establishing a permanent political relationship with the West.
- The third ruler of the Ming Dynasty, the Yongle Emperor, sent his vizier Zheng He – in a fleet of 1500-ton ships – on seven voyages of exploration and tribute collection (1405-1423 AD) that made it as far as East Africa: the only explorations in Chinese history.

Although China was capable of communication, her communicative phase was short: $L = 18$ years, 0.5% of the possible lifetime.

6

Question!

If there are other civilizations nearby in the Galaxy, should we try to communicate with them?

A. Yes
B. No

7

Overpopulation & collapse

Thomas Malthus famously remarked (1798) that population seems inevitably to increase faster than its means of subsistence – food – can increase:

> "The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race… should [armies] fail in [their] war of extermination, sickly seasons, epidemics, pestilence, and plague advance in terrific array, and sweep off their thousands and tens of thousands. Should access be still incomplete, gigantic inevitable famine stalks in the rear, and with one mighty blow levels the population with the food of the world."

On this basis, Malthus expressed worries about the viability of several nations, and one of his chief worries was Ireland. Soon, Ireland became the exemplar of this form of collapse.

8

Overpopulation & collapse – Ireland

From the early 1700s on, Ireland, with a population of 7-8 million, was on the edge of being able to feed itself. Ireland's poor relied almost exclusively on potatoes for nutrition.

When a blight destroyed the potato crop two years in a row (1845-46), two million people died, three million emigrated, and the Irish nation was virtually destroyed.

Although Malthus was certainly correct about Ireland, there was an interesting additional evolutionary factor at play: only a few varieties of the ~100 different strains of potatoes in the Andes had made it to Europe.

- This left the crops vulnerable to a well-aimed disease that would not have been a problem in a more diverse plant population.

9

Overpopulation & collapse

Two examples on a larger scale:

- By the end of the third century AD, both the Roman and Han Chinese empires were populated near the limit of their subsistence.
- Repeated epidemics and probably a minor cooling of global climate sent both empires into tailspins from which neither recovered; their civilizations and influence were destroyed.

Earth can feed a maximum of about 20 billion; the current population is over 7.7 billion and doubling every 55 years.

10

Resource depletion & collapse

Resource-abuse-related micro-examples in the collapse of civilizations on Earth (Diamond 2004):

- On **Easter Island**, Polynesian colonists, unused to the timescale for tree growth in more temperate climates, systematically deforested the island and left themselves without transportation or fishing vessels. Probably about a 70% population loss.
- The **Greenland Norse** practiced forms of farming, shipbuilding, and weaponry, developed in Scandinavia, that were unsustainable in Greenland; unsustainability became catastrophic when they ran out of wood and iron, ceased to be visited from Iceland, and endured worsening climate (the Little Ice Age) in the late 15th century.

11

Resource depletion & collapse

Globally, we are now using technology that is based upon access to resources we are using unsustainably, mostly in the realm of nonrenewable resources like petroleum and natural gas. Petrochemicals provide, among other things:

- Our highest-energy-density fuels, without which aviation would be much more difficult
- Plastics, without which modern technology is scarcely imaginable
- Fertilizers, important in maintaining the high crop yields upon which we have come to depend

It is possible that the exhaustion of this resource would lead to a sudden collapse of either technology or population.

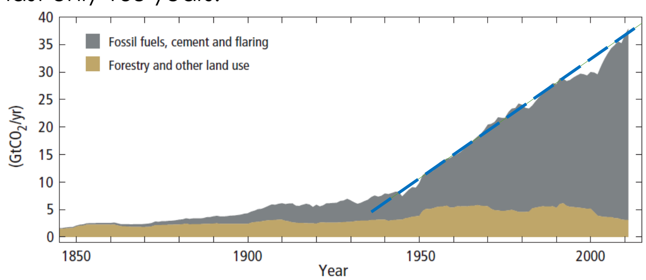
12

Resource depletion & collapse

Approximately 10^4 petagrams (Pg) of carbon in the form of coal, oil and natural gas is an upper limit on the current underground supply.

At the moment, we use 7.7 Pg of this per year, mostly for energy. At this rate, the fossil hydrocarbons will last 1300 years.

But, the burn rate is increasing roughly linearly, doubling every 22 years. At this rate, 10,000 Pg would last only 138 years.



Global anthropogenic CO_2 emissions (IPCC #5)

14

Destruction of habitability

For over sixty years, humans have held the power to destroy their habitat by three primary means. We will discuss two (the third is the pollution of air and fresh water).

1. Weapons of mass destruction, such as **nuclear weapons**. From 1965 to 1985, the arsenals of the USA and USSR contained about 60,000 warheads, totaling 40,000 megatons. This is the same as
   - Five Class 5 hurricanes, though more concentrated
   - Impact of a few-km diameter asteroid
   - 200 large volcanic explosions (e.g. Krakatoa 1883)

   But, worst of all,
   - Ten times as much as would completely destroy every large city in each country

15

Destruction of habitability

Results of all-out nuclear war

- Aimed preferentially at cities, so population would be preferentially destroyed
- H-bomb-destroyed cities would very efficiently turn to dust, which would scatter and rise into the atmosphere
- This would prevent the sunlight from reaching the ground (50-90% of it), causing temperatures to drop and stay low for several years: **nuclear winter**
- The nuclear winter would cause a progressive collapse of the food chain, very similar to prehistoric extinctions
- This outcome is accurately portrayed in many movies

16

Question!

What do you think will get us first?

A. Overpopulation
B. Exhaustion of energy resources
C. Exhaustion of other technological necessities
D. Nuclear destruction
E. Other

17

Destruction of habitability

2. **Emission of carbon dioxide gas.** The concentration of CO_2 in the atmosphere and the oceans is governed by the following interlocking cycles:
   - **Plants.** CO_2 is removed from the atmosphere by **photosynthesis** at a rate proportional to the number of plants.
     - In turn, plants return CO_2 to the atmosphere as they use photosynthetic energy (**respiration**).
     - But not all: plants **sequester carbon** as they grow and add to the Earth's soil when they die – as soil, and over longer terms as **coal, oil, and natural gas**.

18

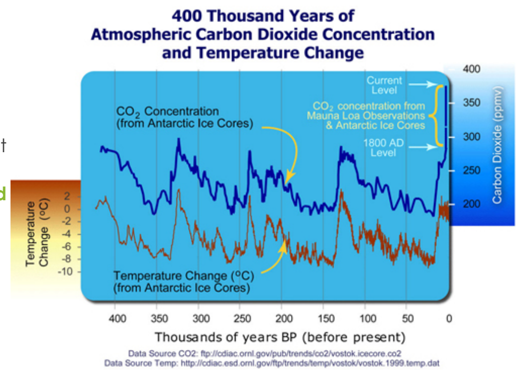
Destruction of habitability

- **Ocean.** CO_2 dissolves in water, producing carbonic acid (H_2CO_3), or in solution hydronium (H_3O^+) and bicarbonate (HCO_3^-).
  - Not that readily in ocean water: only about 10% of an increase in atmospheric CO_2 gets dissolved (Revelle & Suess 1957), but enough that the near-surface acidity of the ocean is significantly affected.
    - About 40% of the CO_2 added since 1750 is still in the atmosphere; 30% is dissolved in the oceans.
  - Carbonic acid in rain weathers rocks and adds calcium to the runoff.
  - In addition to photosynthesis, several microorganisms in the ocean **sequester carbon** by converting calcium and carbonic acid into calcium carbonate ($CaCO_3$) in shells and coral. They also respire some CO_2.
  - Some of the shells and coral are **subducted** on ~10 Myr timescales, along with the rest of the ocean plates; some is included as **limestone** in the continental plates.

19

Destruction of habitability

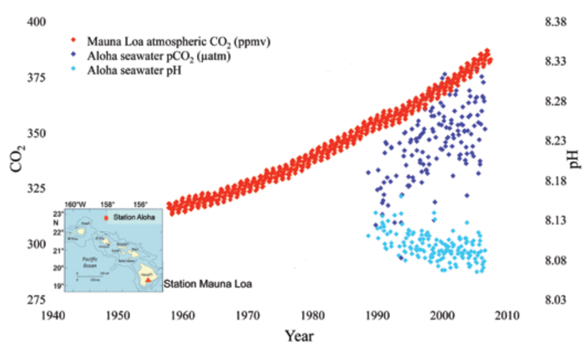
- **Burning fossil fuels and carbonate rocks.** In all, about 20% of the carbon underground is currently in the form of coal, oil, and gas; most of the rest is in the form of limestone, which is burned to make concrete. This sequestration of about 93% of Earth's carbon was vital in producing the atmospheric conditions in which our species evolved. But now,
  - We burn fossil fuels into CO_2, currently at a rate of 7.7×10^{15} g (7.7 Pg = petagrams) of C per year.
  - Concrete manufacturing adds another 0.3 Pg/yr of C in CO_2.
  - This is about 4% of the annual traffic of carbon among the air, plants/soil, and the ocean…
  - …and is added too fast to be completely taken up by plants and the ocean, so 70-80% of it stays in the atmosphere.
  - Using air bubbles trapped in ice, we can accurately measure the concentration of CO_2 in the atmosphere for about the past 400,000 years.
  - Such measurements show that **atmospheric CO_2 has increased very sharply since the Industrial Revolution** and is now the highest on record.
  - This increase can confidently be ascribed to fossil-fuel burning.



20

Destruction of habitability

- Why is this a worry?
  - Dissolved CO_2 is reducing oceanic pH significantly and steadily.
    - In concert with this, **acidification** has caused a decline in many aquatic species – in particular, many species, like coral, that are involved in turning carbonate ions into carbonate minerals.
  - More famously, the global surface temperature – which is also measurable for the past several hundred thousand years – has also increased to historic highs over the last 100+ years in step with the atmospheric CO_2 increases.
- There is no previous **global warming** of the observed magnitude for hundreds of thousands of years.



Doney et al. (2009)

21

Destruction of habitability

- If the current trend of oceanic pH keeps up, a substantial fraction of ocean life will die and the global food chain will collapse on a relatively short time scale.
- If global warming keeps up, the polar ice caps will vanish, raising the sea level by hundreds of meters, rendering vast areas at low latitudes uninhabitable.
  - The gains in habitable areas at the poles would not offset the losses at the lower latitudes.
- Global warming is caused by the **greenhouse effect** of the additional atmospheric CO_2. It is possible, though considered unlikely, that a **runaway greenhouse effect** could result from putting a large fraction of the underground carbon back into the atmosphere.
  - That would make Earth like Venus: completely uninhabitable.

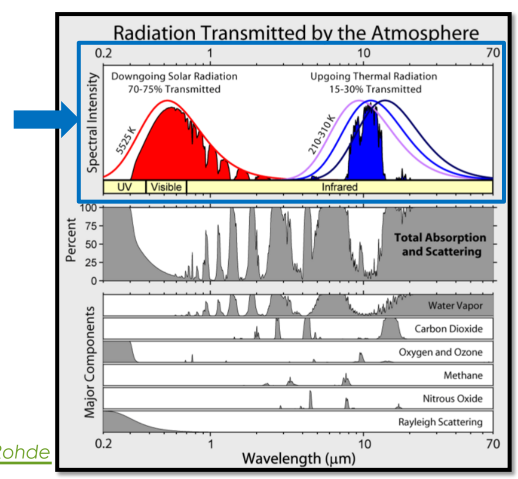
23

The greenhouse effect

As we saw early in the semester, the planets emit most of their light at infrared wavelengths.

The rocky planets would all be brightest near a wavelength of 10 μm.

Solar heating arrives mostly at visible wavelengths, where the atmosphere is transparent.



Created for Global Warming Art by Robert A. Rohde

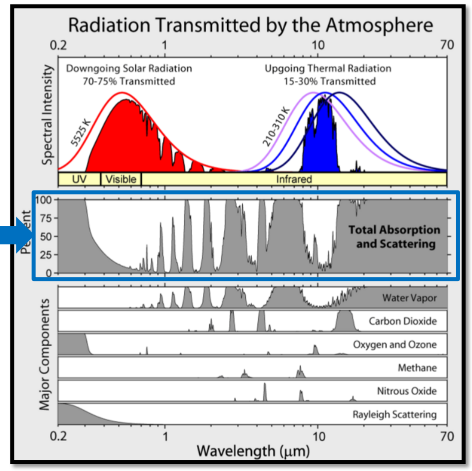
25

The greenhouse effect

Infrared light is absorbed very strongly by molecules in the atmosphere, notably by water and CO_2.

- Some CO_2 is traded for methane (CH_4) in animals and decaying vegetation.

Light from the surface can only escape directly into outer space through "windows," of which the most important lie at wavelengths 8-13, 4.4-5, and 3-4.2 μm.



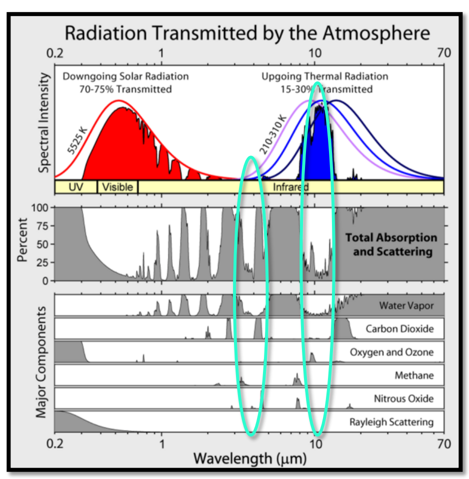
26

The greenhouse effect

Increasing CO_2 per H_2O in the atmosphere tends to close the 3-5 and 8-13 μm windows.

- Methane absorption also narrows these windows, but CO_2 is the big malefactor.

Hotter blackbodies shine more at shorter wavelengths, so if not enough light escapes and 3-5 and 8-13 μm, the **surface heats up** until enough of the emission leaks out in the shorter-wavelength windows.



27

The greenhouse effect

Water produces the strongest greenhouse effect. **If there is liquid water on the surface,** water's greenhouse effect can be self-stabilizing, as water droplets form clouds that reflect the sunlight, depending upon the altitude at which the clouds form. (CO_2 and CH_4 form neither droplets nor clouds at the pressures and temperatures of Earth's atmosphere.)

If temperatures rise,

- ⇒More water evaporates into the atmosphere
- ⇒More clouds form
- ⇒Albedo increases
- ⇒Less sunlight reaches the surface
- ⇒Temperature drops

On Venus, sunlight and the greenhouse effect were sufficient to evaporate all of the water, leaving no liquid bodies on the surface: all water *and* all CO_2 stayed in the atmosphere.

28

The greenhouse effect on Venus

Under solar ultraviolet illumination, water molecules high in the atmosphere readily dissociate, producing atomic hydrogen and oxygen.

- Oxygen goes on to rapidly react with other molecules; hydrogen, not so much.

Hydrogen is too light to be retained by Venus's gravity (or Earth's), so it escaped relatively quickly.

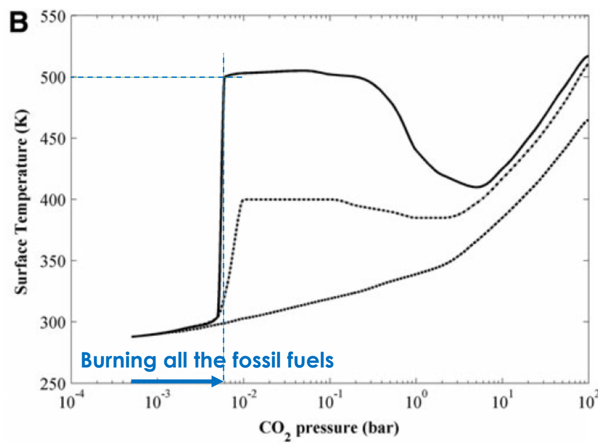
- Soon, there was no more water, or possibilities for making water: a dead world.
- All the carbon and oxygen wound up in CO_2, the atmosphere pressurized, and the greenhouse effect cranked up to 735 K: a *sterilized* world.

29

The greenhouse effect

Recent estimates for greenhouse-effect increase with increasing atmospheric CO_2 (Ramirez et al. 2014):

- Burning all our gas, oil, and coal reserves at the present rate would increase the atmospheric CO_2 by a factor of 12, possibly raising the surface temperature to about 500 K (440°F).
- This would sterilize the Earth, but it would not lead to a loss of the planet's water. Life could try again someday.



30

What do you think will get us first?

Question!

A. Killing the oceans
B. Melting the ice caps and restricting habitats to the poles
C. Runaway greenhouse effect
D. All of the above will happen in rapid sequence.
E. None, as we will prevent them.
F. Who cares, the robots will have taken over by then.

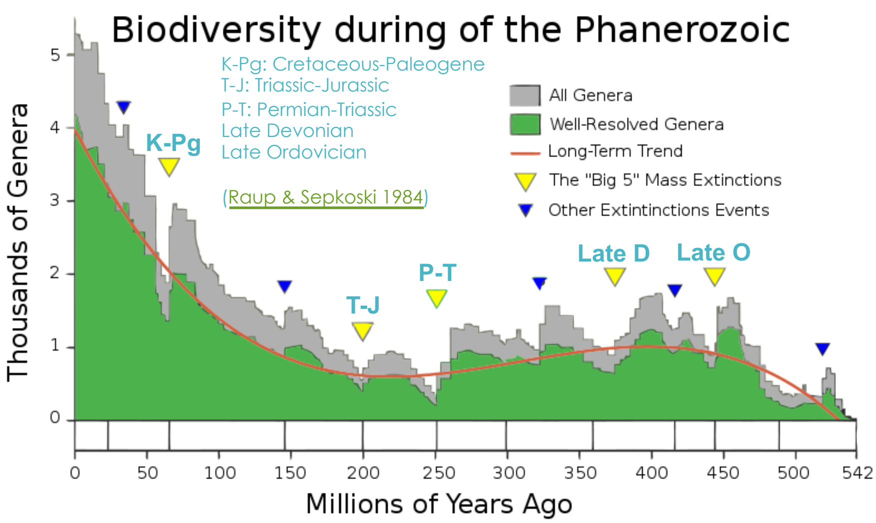
31

What self-inflictable danger could end our civilization the quickest?

Question!

A. All-out nuclear war
B. Ocean acidification
C. Runaway greenhouse effect
D. Overpopulation
E. Resource depletion

32



Natural disasters

Of course, it is possible for civilizations to not shoot themselves in the foot and instead be destroyed by natural processes. Take the pre-civilization mass extinctions, for example.

33

Natural disasters

What effect would these events have had on our civilization? Can we learn from them about the rate at which threats to civilizations happen? That depends upon what caused them.

In the three most sudden and severe extinctions, **global climate change** seems to be the proximate cause, which could kill us, too.

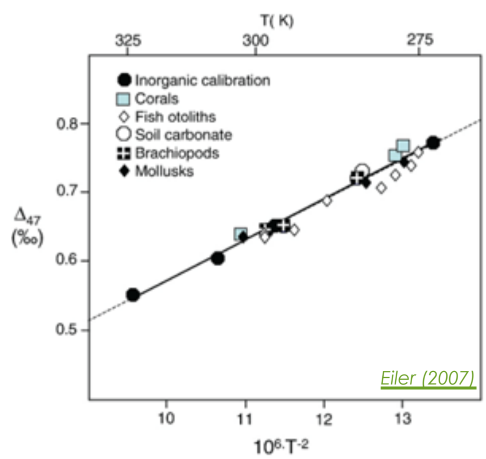
- **Late Ordovician** (LO): 445 Myr ago, 50% of genera extinct. Probably before there were any plants or animals on land.
- **Permian-Triassic** (P-T): 252 Myr ago, 80% of genera extinct
- **Cretaceous-Paleogene** (K-Pg): 65 Myr ago, 50% of genera extinct. Until recently, this was called the Cretaceous-Tertiary (K-T).

In turn, we need to know the cause for the sudden, global climate change, which in these three cases can be narrowed down to one or two processes. (The reason tends to be less clear for the other mass extinctions.)

Measuring paleoclimatic conditions

By measurement of rare isotope abundances in carbonaceous minerals such as calcium carbonate, geologists can determine such facts as the global temperature, rate of production of photosynthesizing organisms, and the pH and oxygen content of the oceans.

- Examples: $^{18}O/^{16}O$, $^{13}C/^{12}C$, $^{34}S/^{32}S$, or ^{13}C and ^{18}O together (“Δ_{47}”)
- This technique works because these minerals are made in the oceans by corals and mollusks out of the ocean water and dissolved CO_2, Ca, etc.
- Example: the vapor pressure of $H_2{}^{18}O$ decreases with increasing temperature much more sharply than $H_2{}^{16}O$ simply because it is heavier; thus, larger $^{18}O/^{16}O$ in carbonates generally means lower ocean temperatures.

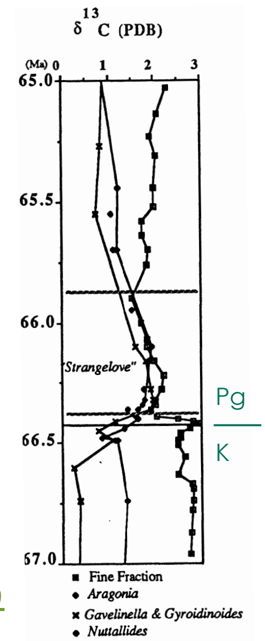


Global climate through the K-Pg boundary

The vicinity of the K-Pg boundary features global cooling followed by global warming, neither of which are very large, but one sudden, short series of events:

- A large drop in ocean-floor organic carbon, indicating a lengthy interruption in photosynthesis by marine organisms
- A large rise in dissolved CO_2 (acidification) and drop in dissolved O_2 (anoxia): so-called Strangelove-ocean conditions, lasting about 500 kyr.
- Large amounts of soot at the K-Pg boundary, which have been suspected to be from global wildfires.

Thus: collapse of the food chain, and starvation/suffocation/immolation of plants and animals.



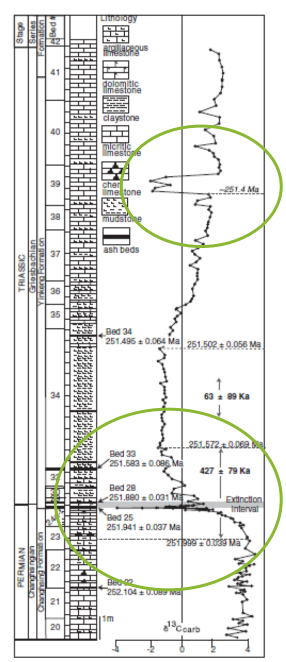
Zachos et al. (1988)

36

Global climate through the P-T boundary

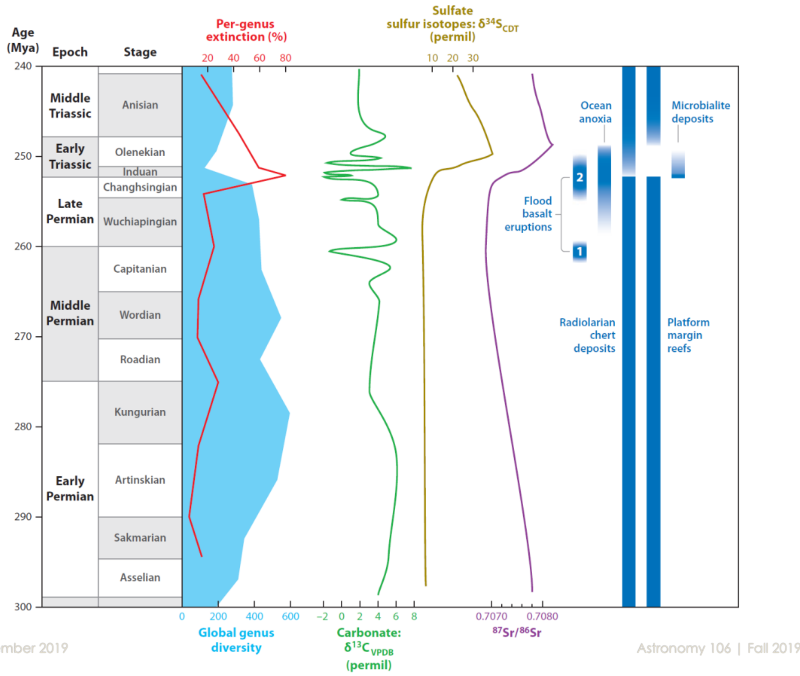
The P-T extinction, the first pulse of which took only about 60 kyr, took place during sudden, extreme global warming:

- The average ocean temperature rose abruptly by 8℃ (McElwain & Punyasena 2007); tropical waters reached 40℃ (104°F; Sun et al. 2012).
- This would have taken an atmospheric CO_2 increase to about 2000 ppm, seven times the pre-industrial value.
- This is consistent with the large increase observed in oceanic C, accompanied by a large influx of S: the ocean was anoxic and acidified (Payne & Clapham 2012).



Burgess et al. 2014

37



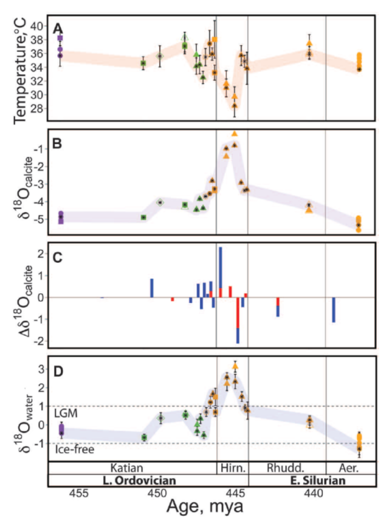
Global climate through the P-T boundary

Payne & Clapham (2012)

Global climate through the LO boundary

In contrast, the LO extinction occurred during an ice age that intruded on greenhouse conditions for about 1.5 Myr.

- This was before land plants and the sequestration of 20% of Earth's carbon into coal, oil, and gas; atmospheric CO_2 was 4200 ppm, about 17 times the pre-industrial concentration.
- Abruptly, the average ocean temperature cooled by about 8°C in two pulses separated by 1.5 Myr.
- Massive ice caps formed, similar to Pleistocene ice caps, reducing the sea level by 100-200 meters.

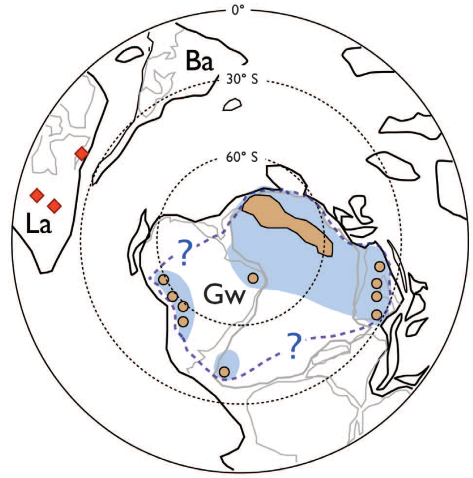


Finnegan et al. (2011)

Global climate through the LO boundary

At the time, most of the biomass was in the shallow continental shelf / submerged continental plate regions close to the equator.

Rapid sea level reduction left marine life high and dry. Many species evolving toward survival of dry conditions were finished off as the seas returned between the two ice-age pulses.



Finnegan et al. 2011
Ron Blakey/Colorado Plateau Geosystems

The ultimate causes

These climate changes and mass extinctions have been studied and debated for decades, and we are zeroing in on the following explanations:

- The P-T mass extinction – worst of them all – seems to have been caused by **supervolcanism**: the basaltic magma flooding that created the Siberian Traps and its unfortunate interaction with large amounts of carbonate rock on the surface.
- The origin of the K-Pg mass extinction seems clearest: it was triggered by the **impact of an asteroid** about 10 km in diameter.
- The LO extinction lacks a clear explanation. It is currently thought to probably have been caused by **climate instability**, triggered in part by an unfortunate arrangement of the continents.

Energy scale & familiar units

In the field of large-scale destruction, popular units of energy are the **megaton** (Mt) and the **gigaton** (Gt): the energy released upon detonation of one million or one billion metric tons of trinitrotoluene (TNT), respectively.

$$\begin{aligned} 1\ \mathrm{Mt} &= 4.184 \times 10^{22}\ \mathrm{erg} \\ &= 4.184 \times 10^{15}\ \mathrm{J} \\ &= 10^{12}\ \mathrm{Cal} \\ 1\ \mathrm{Gt} &= 10^{3}\ \mathrm{Mt} \end{aligned}$$

The world's nuclear arsenal has a yield of about 40,000 Mt = 40 Gt.

Mushroom cloud from a 15-Mt hydrogen bomb: Castle Bravo, Bikini Atoll, 1954 (US DoD, DoE)

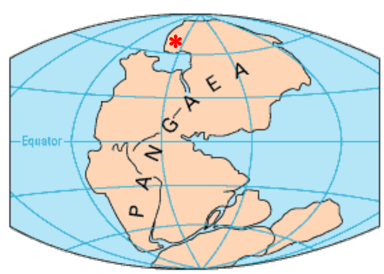
42

Supervolcanism & P-T

Precisely in unison with the P-T mass extinction was one of the largest volcanic eruptions in Earth's history. Its remains are called the **Siberian Traps** today.

The radiometric age of the basalt spans about one million years, which spans the two pulses of extinction (Reichow et al. 2009).

The hot magma outgassed methane and CO_2; it also flowed over nearby carbonate rock formations and burnt them to CO_2 as well. As much as 30,000 Pg of C went into the atmosphere (Payne & Clapham 2012). (This is about 50% of crustal carbon.)



Late Permian
250 Myr ago

USGS

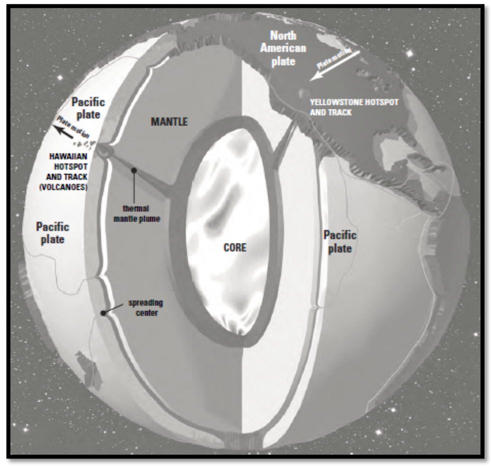
43

The danger from supervolcanism

Volcanoes are found along subduction zones and mid-ocean rifts, but the sites most productive of lava are the **hotspots**: breaks in Earth's crust due to **mantle plumes**, welling up through the mantle from points near its base.

There are two notorious hotspots on US soil:

- Hawai'i, which releases energy rather gently
- Yellowstone, which does not



USGS

45

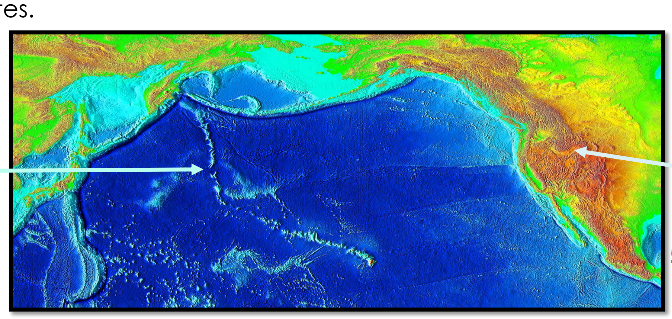
The danger from supervolcanism

Hotspots generally spew magma onto the crustal surface at 0.1 km^3 of basalt per year, with bursts of activity in excess of 1 km^3.

Siberian Traps magmatism averaged 5 km^3 per year in the Myr around the P-T boundary.

Hotspots *generally* wander little on tectonic time scales (see, however, Tarduno et al. 2003); their volcanism leaves **island/seamount chains** and **large igneous provinces** on the moving plates.

Hawaiian hotspot track: Hawaiian islands, Emperor seamounts



Yellowstone hotspot track

USGS

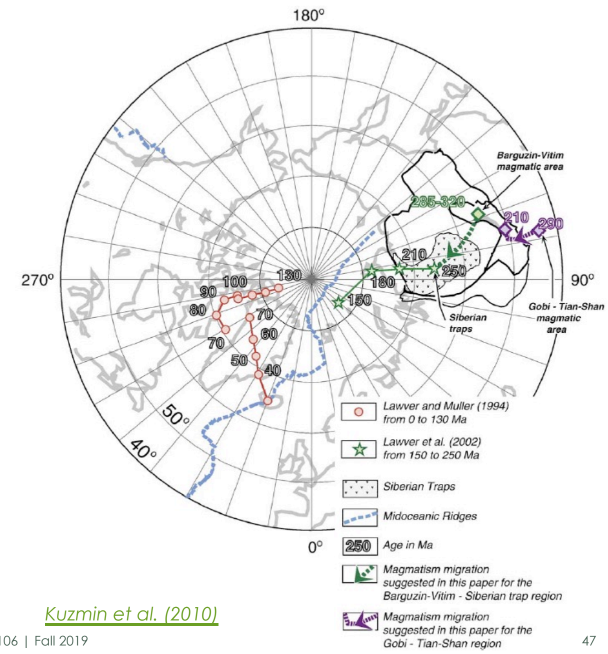
46

The danger from supervolcanism

The Siberian Traps are associated with the Iceland hotspot (still mildly controversially), currently underneath the Mid-Atlantic Ridge and engaged in the construction of Iceland.

Magma flows on Iceland have spiked briefly at over 20 km^3 per year in 934 and 1783.

- Fumes from the 1783 eruption killed half of the livestock in Iceland, leading to a famine killing a quarter of the people.



Kuzmin et al. (2010)

47

Large igneous provinces

Igneous province	Age [Myr ago]	Location	Volume [Mkm^3]	Hotspot
Columbia River Basalt Group	16	NW USA	0.2	Yellowstone
Mid-Tertiary ignimbrite flare-up	33	SW USA	5	Raton?
North Atlantic Igneous Province	56	N Atlantic	6.6	Iceland?
Deccan Traps	65	Deccan Plateau, India	1.5	Réunion
Caribbean large igneous province	88	Either side of Panama	4	Galapagos
90 East Ridge – Kerguelen Plateau – Broken Ridge	112	Indian Ocean	17	Kerguelen
Ontong Java – Manihiki – Hikurangi Plateau	121	SW Pacific	60	Louisville
Paraná and Etendeka Traps	133	Brazil, Angola, Namibia	2.3	Tristan da Cunha
Karoo-Ferrar	183	South Africa and Antarctica	2.5	Crozet?
Central Atlantic magmatic province	200	Americas, NW Africa	2	Fernando?
Siberian Traps	250	Siberia	5	Iceland
Emeishan Traps	257	SW China	1	?

48

Large volcanic explosions

Smaller volumes of rock, but rendered disproportionately into high-altitude dust.

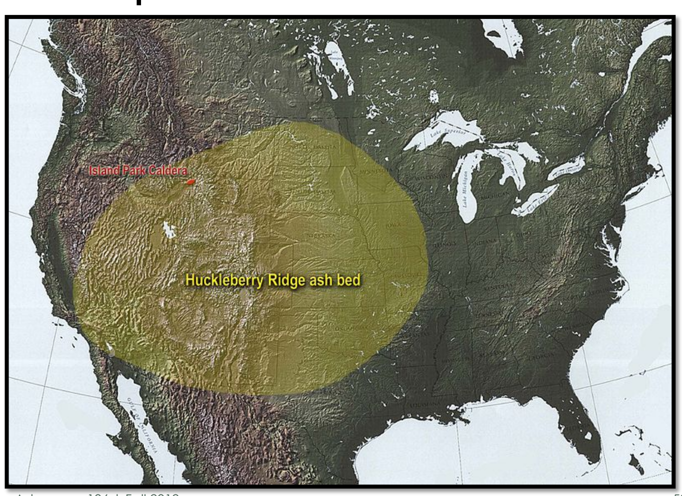
Data: USGS Yellowstone Volcano Observatory and Hawai'i Volcano Observatory

Event	When	Rock displaced [km^3]	Energy released [Mt]
La Garita (Colorado)	27.8 Myr ago	5000	120,000
Yellowstone, Island Park	2.1 Myr ago	2450	58,800
Yellowstone, Mesa Falls	1.3 Myr ago	280	6720
Yellowstone, Lava Creek	0.64 Myr ago	1000	24,000
Toba (Sumatra)	74 kyr ago	2800	67,200
Tambora (Sumbawa)	1815	160	3840
Mt. St. Helens	1980	1	24

49

Large volcanic explosions

The ashfall from the largest Yellowstone explosions covered most of the continental US and gave rise to Pompeii-like death and burial of grazing herds as far away as modern St. Louis.



Distribution of Huckleberry Ridge Tuff: the ashfall of the Island Park (2.1 Myr ago) explosion of the Yellowstone hotspot.

50

The danger from supervolcanism

The only mass extinction tied firmly to hotspot supervolcanism is the P-T. Of course, that was the Big One.

- Eruptions on the scale of 10-20 km^3/yr, sustained for thousands of years, can be dangerous to life on the planet as well as civilization. We should worry about this happening every **50-100 Myr**.
- If Yellowstone were to explode today with Island Park-like violence, it may destroy the United States and reduce worldwide food-generation capacity for many years.
- This could possibly lead to worldwide famine and cultural collapse.
- We should worry about this happening every **2-20 Myr**.

Unfortunately, **there is nothing we can do to prevent supervolcanism**.

51

Asteroid impacts and K-Pg

The K-Pg mass extinction is the best explained because it comes with a smoking gun: it was caused by an asteroid impact (Alvarez et al. 1980, Schulte et al. 2010, Renne et al. 2015) with a yield of approximately 10,000 Gt.

A **worldwide** layer of claystone is found at 65 Myr old that has platinum-group (e.g. iridium) abundance 30-300 times larger than found elsewhere in Earth's crust, but similar to that found in meteorites.

Below this layer are many fossils of non-avian dinosaurs; above it, there are none.

The rock hammer tip indicates the K-Pg boundary as seen south of Starkville, CO (USGS)

52

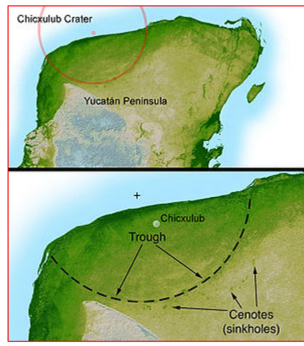
Asteroid impacts and K-Pg

The scene of the crime has been identified with high confidence:

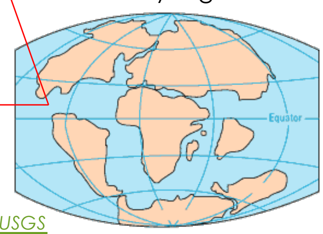
A giant (180 km diameter) impact crater centered roughly on Chicxulub, Yucatan, Mexico, formed precisely 65 Myr ago.

Found around the crater are minerals with evidence of shock heating (e.g. shocked quartz) and with the same extra heavy-metal abundances as the K-Pg boundary.

Clear in the bedrock but mostly covered with sediments.



65 Myr ago



USGS

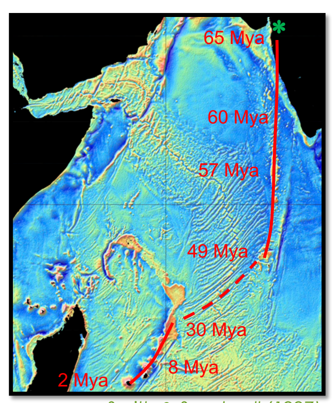
53

Asteroid impacts and K-Pg

The impact took place during a major supervolcanic event: the creation of the Deccan Traps (*), probably by the Réunion hotspot.

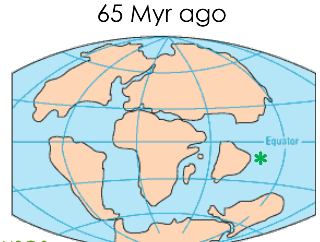
The impact probably influenced the eruption through stimulus of earthquakes worldwide: the magma flow became more explosive, episodic, and productive (Renne et al. 2015).

Recovery from the impact was probably slowed substantially by the effect of this supervolcanism.



Smith & Sandwell (1997)

65 Myr ago



USGS

54

The danger from an asteroid impact

There are hundreds of thousands of asteroids in the Solar System that are larger than 1 km.

Of these, by far the most dangerous are asteroids currently in orbit near Earth, called **near-Earth objects (NEOs)**.

Currently, we have detected 901 near-Earth asteroids with diameters larger than 1 km. Several NASA-funded projects (e.g. Spacewatch and NEOCam) are charged with compiling a complete census, with a goal of finding 90% of the NEOs 140 m or larger.

Manicougan Crater, Quebec (NASA). Diameter = 70 km (lake) to 100 km (rim).

55

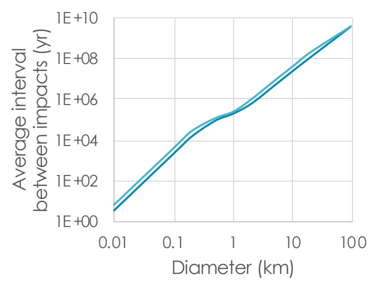
Size*	Examples	Most recent	Planetary effects	Effects on life
Super-colossal $R > 2000$ km	Moon-forming event Mars	4.45×10^9 yr ago	Melts planet	Drives off volatiles Wipes out life on planet
Colossal $R > 700$ km	Pluto largest few KBOs	$\gtrsim 4.3 \times 10^9$ yr ago	Melts crust	Wipes out life on planet
Mammoth $R > 200$ km	4 Vesta 3 other asteroids	$\sim 3.9 \times 10^9$ yr ago	Vaporizes oceans	Life may survive below the surface
Jumbo $R > 70$ km	8 Flora 90 other asteroids	3.8×10^9 yr ago	Vaporizes upper 100 m of oceans	Pressure-cooks troposphere May wipe out photosynthesis
Extra large $R > 30$ km	Comet Hale-Bopp 464 asteroids	$\sim 2 \times 10^9$ yr ago	Heats atmosphere and surface to ~ 1000 K	Continents cauterized
Large $R \gtrsim 10$ km	KT impactor 433 Eros (large NEA) 1211 other asteroids	6.5×10^7 yr ago	Fires, dust, darkness Atmospheric/oceanic chemical changes, large temperature swings	Half of species extinct
Medium $R > 2$ km	1620 Geographos	$\sim 5 \times 10^6$ yr ago	Optically thick dust, substantial cooling Ozone layer threatened	Photosynthesis interrupted Significant extinction
Small $R > 500$ m	~ 1000 NEOs Lake Bosumtwi	$\sim 500{,}000$ yr ago	High altitude dust for months Some cooling	Massive crop failures Civilization threatened
Petite $R > 100$ m	Tunguska event	June 30, 1908	Minor hemispheric dust	Newspaper headlines Romantic sunsets increase birth rate
Sub-Petite $R > 10$ m	Chelyabinsk meteor (20 m; 0.46 Mt yield)	February 15, 2013	Substantial damage to 7200 buildings Broke the internet	112 people hospitalized, mostly from broken glass laceration

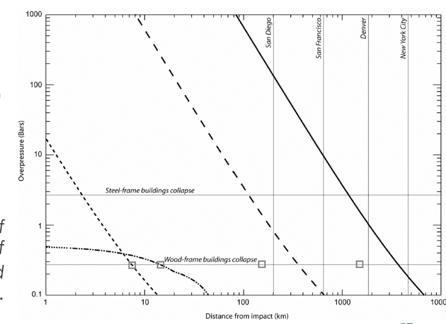
56

The danger from an asteroid impact

Judging from impact craters on the continents, we have to worry about **> 1 km asteroids every few hundred kyr**, and **> 10 km asteroids every few tens of Myr**.

Click here and try for yourself: a calculator for the effects of impacts with user-prescribed initial conditions, courtesy of Jay Melosh and company and based on Collins et al. (2005).





Results for overpressure as a function of distance for an impact in Los Angeles of 75 m stone, 40 m iron, 1.75 km stone and 18 km stone asteroids.

57

The danger from an asteroid impact

These kinds of catastrophes **may be preventable once a civilization reaches our level** or just a little bit higher.

Advanced civilizations will identify and track such objects, as we are beginning to do.

Small objects – less than a km or so – on a collision course with Earth could be safely blown to smithereens by nuclear weapons, converting a significant disaster to an entertaining meteor shower.

Large objects – in the 1-10 km class that could threaten civilization – can be knocked into a non-colliding orbit with a judiciously-placed large explosion (splitting off part of the body), if this can be done sufficiently long enough before the collision.

We currently have the technology to do this, but we have not yet set aside the required resources.

58

Climate instability and LO

There is not an impact or supervolcanic eruption currently linkable to the LO mass extinction.

- This does not mean that there was not one. A crater left in the ocean floor 450 Myr ago would be completely erased by now; ditto a submarine large igneous province.

Other mechanisms are still alive, and the following story of **geography-induced climate instability** has the best support at the moment.

- During the late Ordovician, the mini-supercontinent Gondwana – eventually to be the southern half of Pangaea – drifted over the South Pole.
- This left the entire northern hemisphere oceanic and rearranged the currents in the ocean and the atmosphere.
- At that time, southern summer took place close to Earth's aphelion, instead of today's perihelion; also, the Sun's luminosity was about 4% smaller than it is today.

Climate instability and LO

Under all these conditions, the steady CO_2 concentration of the atmosphere placed it in an **unstable** region of parameter space: a small modification of heat transfer could lead to a large change in other parameters such as global temperature.

- An ineffable characteristic of nonlinear systems with lots of gain

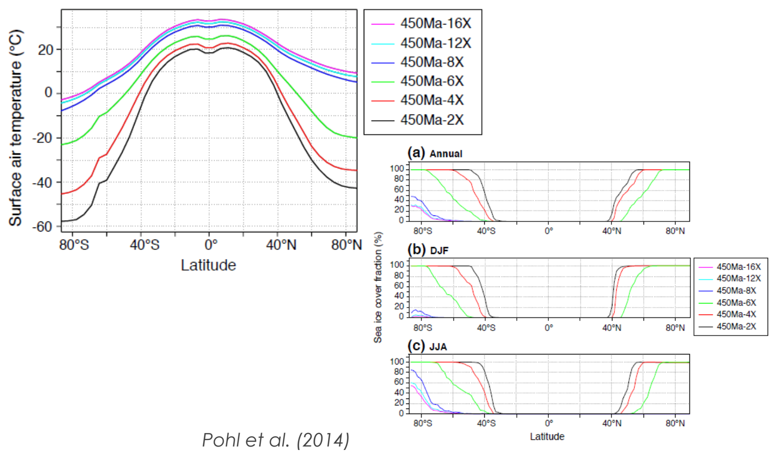
Models show that the slow continental drift of Gondwana could have moved the climate through an instability, lurching between a cold (ice-age) state and a warm (greenhouse) state on Myr time scales (Pohl et al. 2014).

And Gondwana provided a suitable home for an ice cap.

Climate instability and LO

It is difficult to estimate how often this happens, but it would probably not destroy us today:

- Land animals and large marine animals have weathered ice ages just as severe more recently. Ice ages are much less deadly than greenhouse instability!
- We may be in such a phase now. The Pleistocene began concurrently with some major ocean-current rearrangement.



Pohl et al. (2014)

61

The most dangerous natural disaster of all: gamma-ray bursts

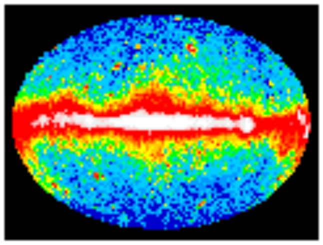
Gamma (γ) rays are the highest energy forms of light.

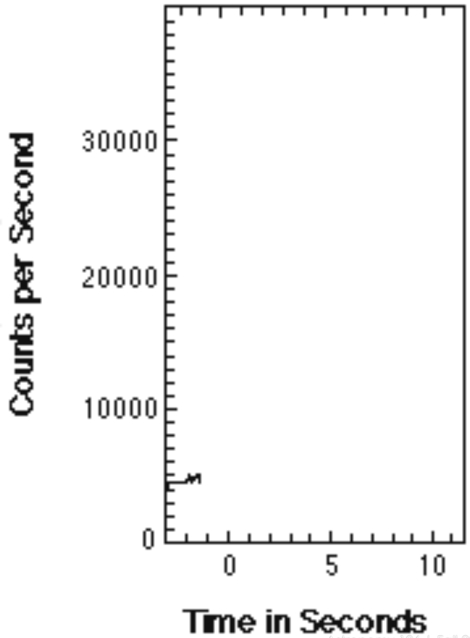
Every few days, a bright starlike source of gamma rays is seen that, for a few seconds, outshines the sum of the rest of the gamma-ray sources in the sky. These are called gamma-ray bursts.

- They are always seen to occur in distant galaxies.
- There are two mechanisms that produce them, both of which involve black hole formation.
  - Supernova of an extremely massive ($> 100M_{\odot}$) star
  - Merger of two neutron stars, or of a neutron star and a black hole

We will cover these much more in Astronomy 102.

62

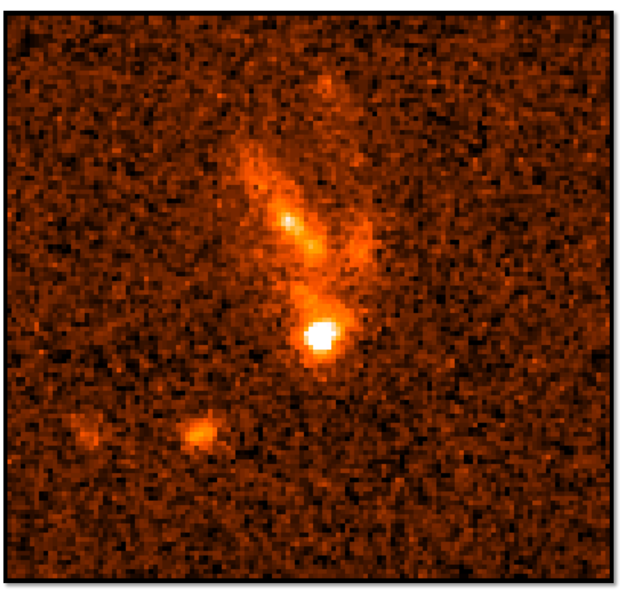




Typical gamma ray burst

Full sky γ-ray image, arranged so that the Milky Way lies along the "equator" (CGRO/NASA)

63



Gamma-ray bursts

Images of the γ-ray burst of January 23, 1999, taken with the STIS instrument on the Hubble Space Telescope 16, 59, and 380 days after the outburst (Andy Fruchter, STScI). It faded at the same pace supernovae do.

64

Gamma-ray bursts

The spectrum of the galaxy in which the γ-ray burst of January 23, 1999 lives indicates that its distance is 9 billion light years.

At that distance, the γ-ray burst amounted to an energy of **3×10^{52} erg** – almost 10^{30} Mt – in γ-rays alone, if it emitted its energy predominantly along its rotational poles and ones of these poles is pointed at us.

For a better scale, this is equivalent to a mass of

$$M = \frac{3\times10^{52}\ \mathrm{erg}}{c^2} = 3.3\times10^{31}\ \mathrm{g} = 0.017M_\odot$$

Or the mass of 17 Jupiters, or 5000 Earths – suddenly, in a span of less than 40 seconds, converted completely into γ-rays.

65

Gamma-ray bursts

A γ-ray burst like that on January 23, 1999 would destroy all life within **several thousand light years** of the burster. If it were 5000 lyr away and pointed at Earth:

- The γ-rays would ionize Earth's atmosphere; the gas would recombine to form nitric oxides, which in turn would eliminate the ozone layer.
- If the γ-rays are followed by a month-long blast of cosmic rays (as models predict), everything within 200 m of the surface would receive a lethal dose of radiation.

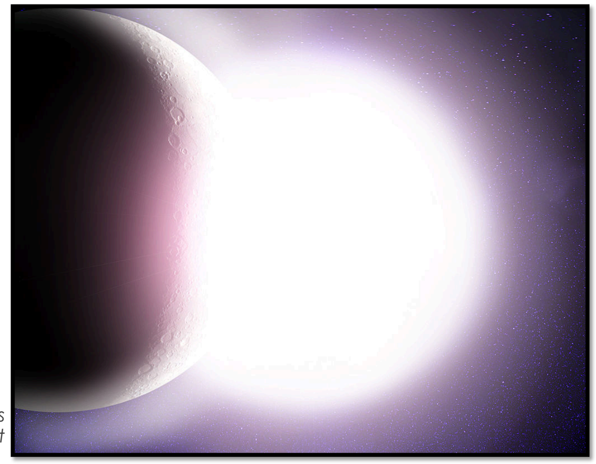
Sky & Telescope, February 1998

66

Gamma-ray bursts

Rating the danger:

- **Nearest binary neutron star**: PSR J0737-3039, 1500 light years away and due to merge 85 million years from now. See Kramer & Stairs (2008).
- **Nearest neutron star – black hole pair**: None known. This does not mean that there are not any.
- **Nearest $> 50M_\odot$ star**: Cygnus OB2 #12, 5220 light years away, but could blow up any minute.



Artist's impression of Cygnus OB2 #12 with a planet