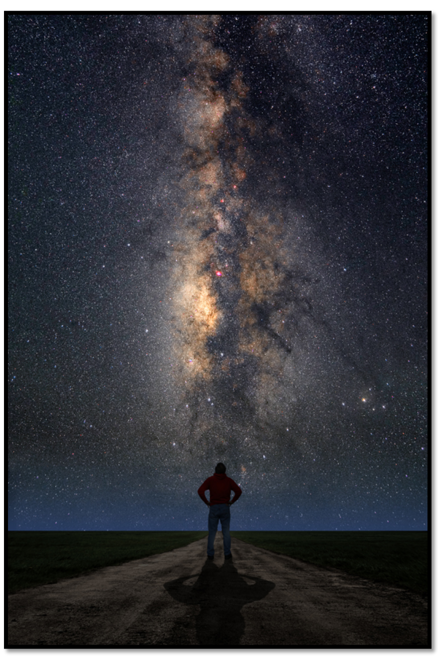
26 November
2019

NATURAL DISASTERS, L, & CONTACT WITH EXTRASOLAR CIVILIZATIONS

Homework #8 due 12/9 (Monday) by 7pm
Exam #3 on 12/10 (Tuesday)

1

Larry Landolfi



Natural disasters, L, & Contact with extrasolar civilizations

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

Drake's L and N

The distances to the nearest extrasolar civilization

Issues of communication, visits, and exploration

The search for extraterrestrial intelligence (SETI)

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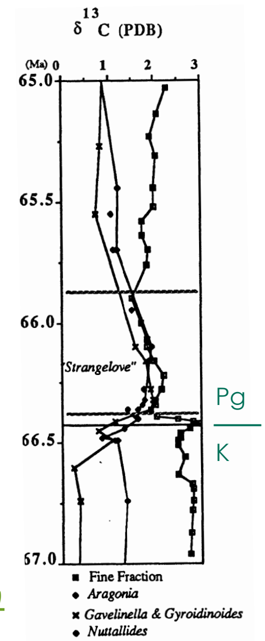
Global climate through the K-Pg boundary

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)

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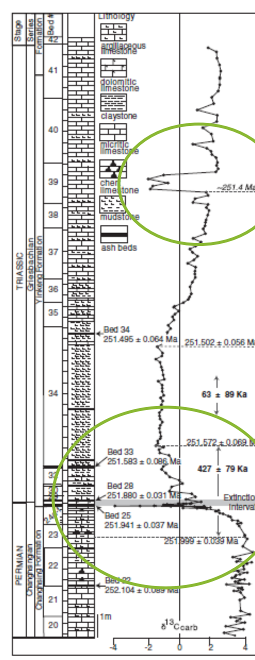
Global climate through the P-T boundary

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 abruptly rose by 8°C (McElwain & Punyasena 2007); tropical waters reached 40°C (104°F; Sun et al. 2012).
- This would have increased the atmospheric CO_2 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

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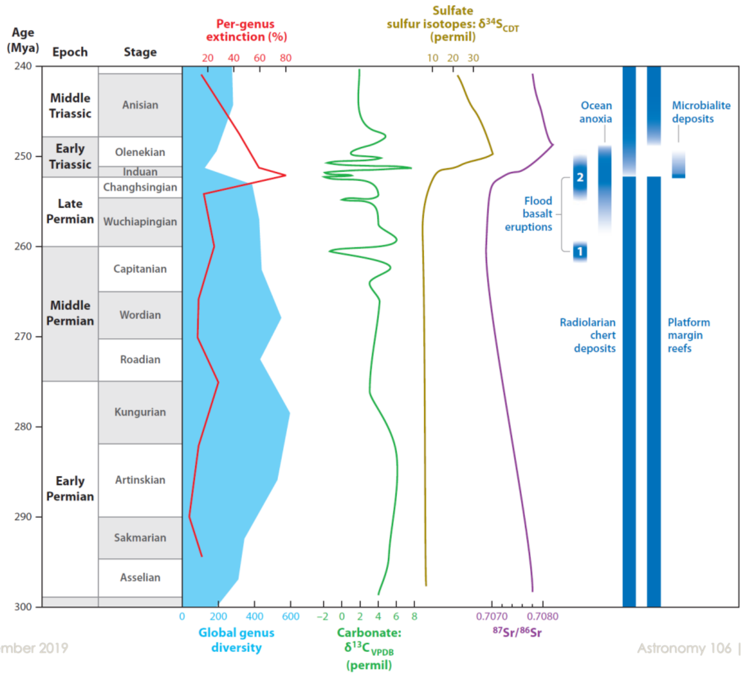

Global climate through the P-T boundary

Payne & Clapham (2012)

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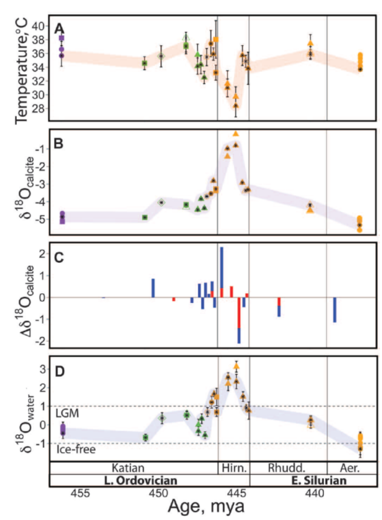
Global climate through the LO boundary

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℃ 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.



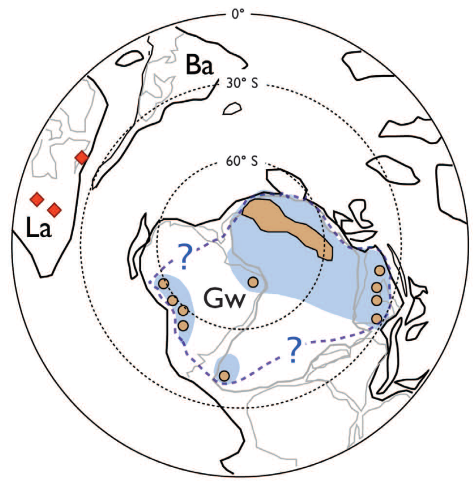
Finnegan et al. (2011)

7

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

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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.

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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)

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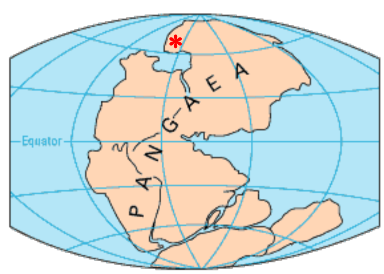
Supervolcanism & P-T

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

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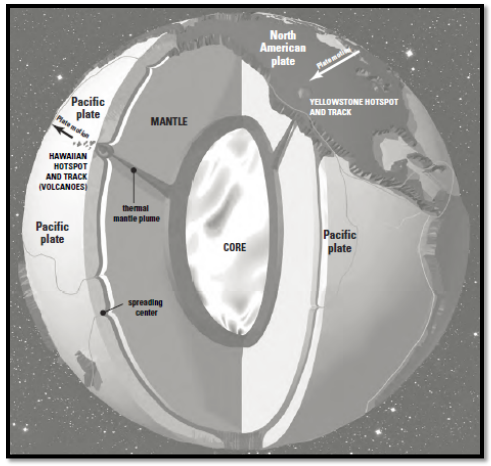
The danger from supervolcanism

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

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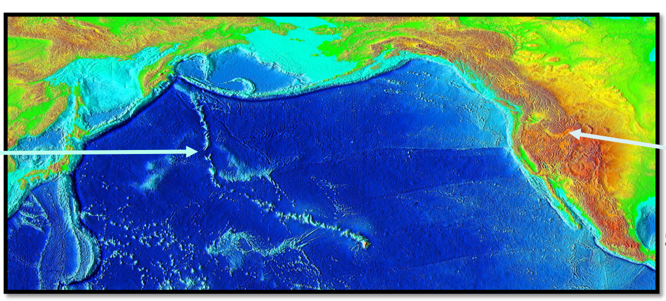
The danger from supervolcanism

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

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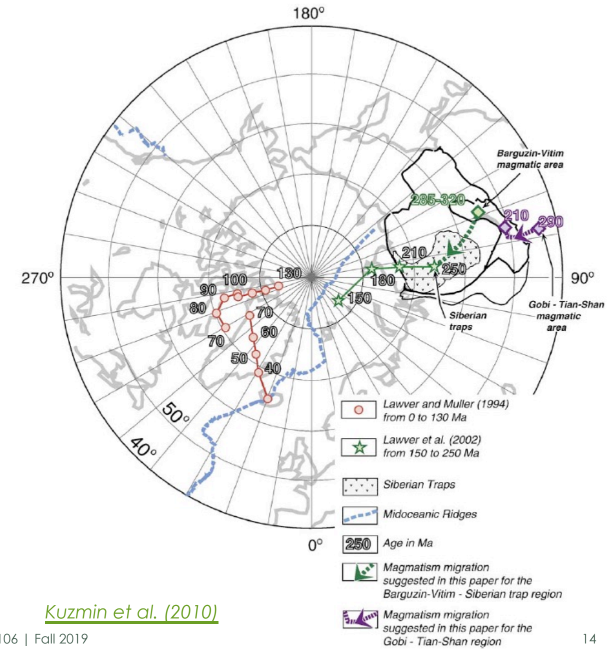
The danger from supervolcanism

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)

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	?

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

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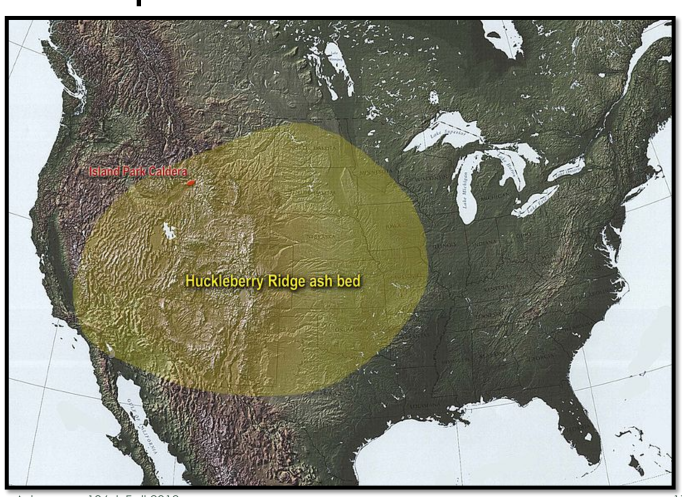
Large volcanic explosions

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.

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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**.

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)

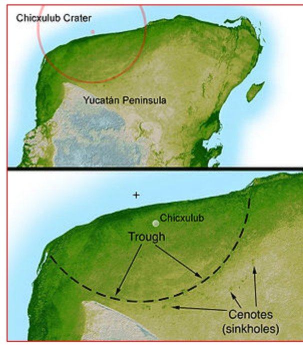
Asteroid impacts and K-Pg

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

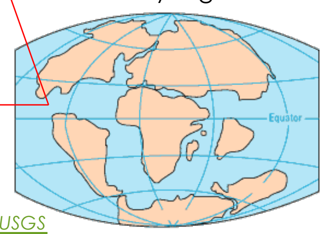
A giant (180 km diameter) impact crater centered roughly on Chicxulub, Yucatan, Mexico, formed precisely 65 Myr ago.

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

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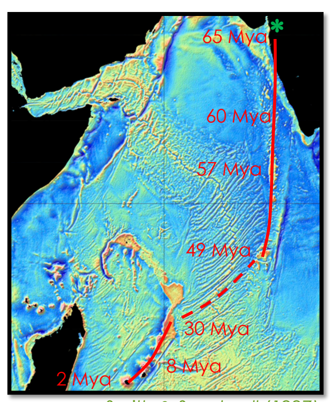
Asteroid impacts and K-Pg

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

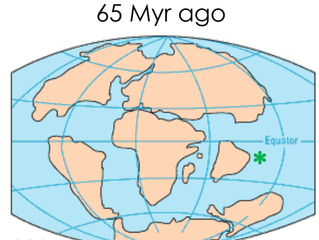
The impact probably influenced the eruption through stimulus of earthquakes worldwide: the magma flow became more explosive, episodic, and productive (Renne et al. 2015).

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



Smith & Sandwell (1997)

65 Myr ago



USGS

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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).

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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	$\gtrsim 4.3\times10^9$ yr ago	Melts crust	Wipes out life on planet
Mammoth $R > 200$ km	4 Vesta 3 other asteroids	$\sim3.9\times10^9$ 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	$\sim2\times10^9$ 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	$\sim5\times10^6$ yr ago	Optically thick dust, substantial cooling Ozone layer threatened	Photosynthesis interrupted Significant extinction
Small $R > 500$ m	~1000 NEOs Lake Bosumtwi	$\sim500{,}000$ 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

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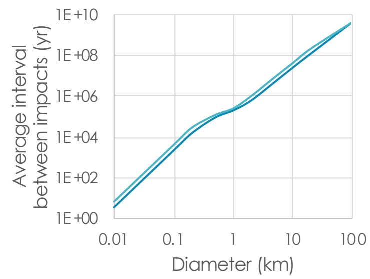
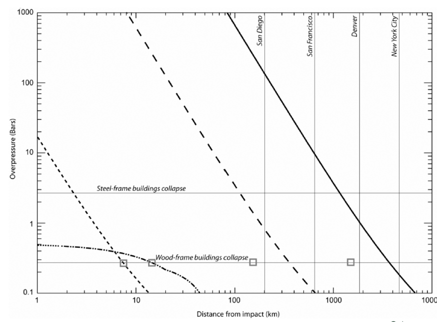
The danger from an asteroid impact

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.

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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.

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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.

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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.

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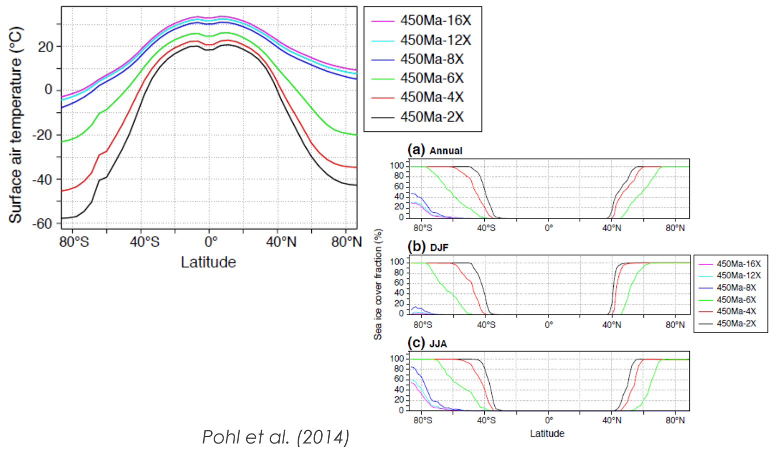
Climate instability and LO

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)

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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.

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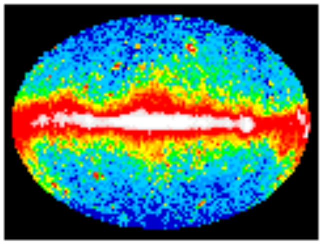

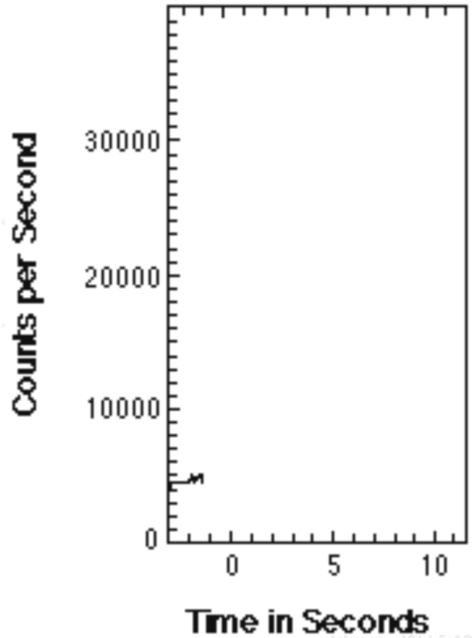

Typical gamma ray burst

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

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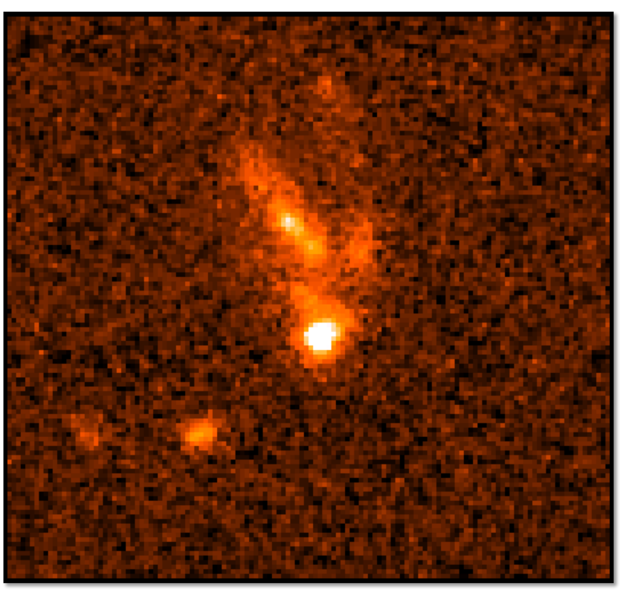

Gamma-ray bursts

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.

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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 that are suddenly, in a span of less than 40 seconds, converted completely into γ-rays.

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Gamma-ray bursts

A γ-ray burst like that on January 23, 1999 would destroy all life within **several thousand light years** of the source. 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*

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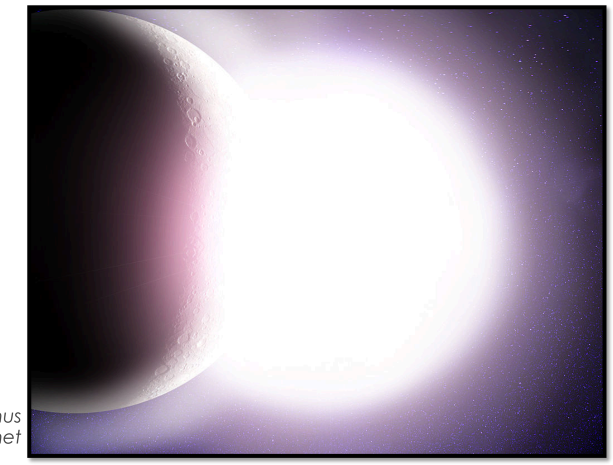
Gamma-ray bursts

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

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Question!

Which natural disaster is likely to threaten civilizations on Earth first?

A. Supervolcanism
B. Asteroid impact
C. Climate change
D. Gamma-ray burst
E. Expiration of the Sun

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Recap of Drake Equation quantities so far

Quantity		Likely range	Our best guess
Star formation rate	R_*	8-32 per year	16 per year
Fraction of stars with planets	f_p	$f_p > 0.75$	1.0
Number of habitable planets per planetary system	n_e	0.25 ± 0.1	0.25
Fraction of habitable planets that evolve life	f_l	0.3 ± 0.2	0.36
Fraction of life-evolutions that evolve intelligence	f_i	$10^{-7} < f_i < 0.1$	0.003
Fraction of intelligence-evolutions that evolve technological civilizations	f_c	$0.01 < f_c < 1$	0.5
Multiplied together: $\frac{N}{L} = R_* f_p n_e f_l f_i f_c$		$10^{-10} < \frac{N}{L} < 0.6$ per year	2.2×10^{-3} per year

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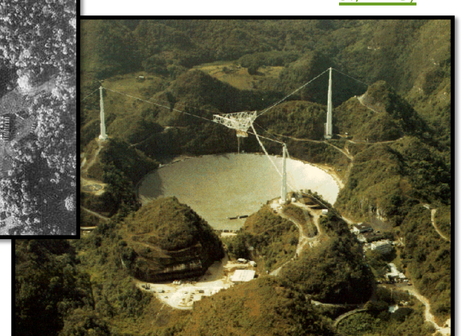
L: The lifetime of communicable technological civilizations

We became a **communicable** civilization – able to broadcast signals detectable from nearby star systems – almost simultaneously with developing several means of wiping ourselves out. For example:

- 1962: Cuban missile crisis, very close to WWIII
- 1963: 305-meter radar telescope dedicated at Arecibo, Puerto Rico (the largest on Earth until 2016)

Soviet nuclear missiles in Cuba, 1962 (NSA)

Arecibo Observatory, 1963 (Cornell U./NAIC)



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L

How long until we run a huge risk of the various catastrophes?

- Nuclear destruction: 0 years
- Overpopulation: 200 years
- CO_2 ocean acidification and/or lethal greenhouse effect: 300 years
- Resource exhaustion: 300 years
- Supervolcanism: 50 Myr
- > 10 km asteroid impact: 50 Myr (Preventable by sufficiently clever, nuclear-capable civilization)
- Gamma-ray burst: 100 Myr, only if aimed at us
- Uninhabitable due to increased solar luminosity: 1.5 Gyr

A generous estimate of $L = 1000$ yr

Median around 100 Myr

The two ranges of L and N

We estimate that technological civilizations like ours have a substantial probability of destroying themselves within several hundred years of communicability.

But if they live through that – and especially if they learn to protect themselves from asteroid impact, which seems likely – then nothing would destroy them within about 100 Myr.

- And by then they seem likely to have found something to do about supervolcanism, and therefore last until their star dies: $L = 1.5$ Gyr.

If either **all** civilizations die of the Catastrophes or **all** live through them, we get these two values:

$$L = 1000\ yr \implies N = R_* f_p n_e f_l f_i f_c L = 2 \quad \textbf{Pessimistic}$$
$$L = 1.5\ Gyr \implies N = R_* f_p n_e f_l f_i f_c L = 3{\times}10^6 \quad \textbf{Optimistic}$$

The two ranges of L and N

So if **none of the Milky Way's civilizations were to make it past the self-inflicted catastrophes, there would only be a few communicable civilizations at present**.

But if **a substantial fraction of these civilizations were to run the gauntlet and live, then there would be somewhere around one million communicable civilizations at present**.

This means that, if there are lots of civilizations in the Galaxy, most of them are more advanced than ours since they have already lived through the catastrophes.

- **Example**: Suppose that half make it through the self-inflicted catastrophes and half do not; then the real N is half of the sum of these previous results:

$$N = \frac{1}{2}(2 + 3\times10^6) = 1 + 1.5\times10^6 \approx 1.5\times10^6$$

Us, and one million and a half more advanced civilizations

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Stephen Hawking thought that it would be dangerous to communicate with extraterrestrial civilizations because they are likely to be more advanced than us. Do you agree?

Question!

A. Yes. They will come take our resources and assimilate us if they know we are here.
B. No. They know our planet is here anyway without our call, and there are many resource-filled planets closer to them.
C. Yes. They will add us to the Galactic equivalent of a zoo.
D. No. Advanced civilizations might be able to help us avoid Catastrophe.

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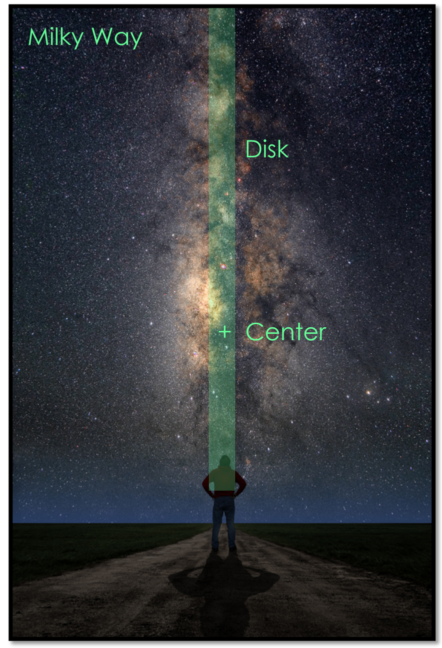
How far to the next civilization?

Population I stars would seem to host most of our galaxy's planets, since they contain a higher abundance of the heavy elements.

Pop I is confined to the **disk** of the Milky Way galaxy: typically, these stars lie within $H = 330$ light years (lyr) of the plane that bisects the Galaxy.



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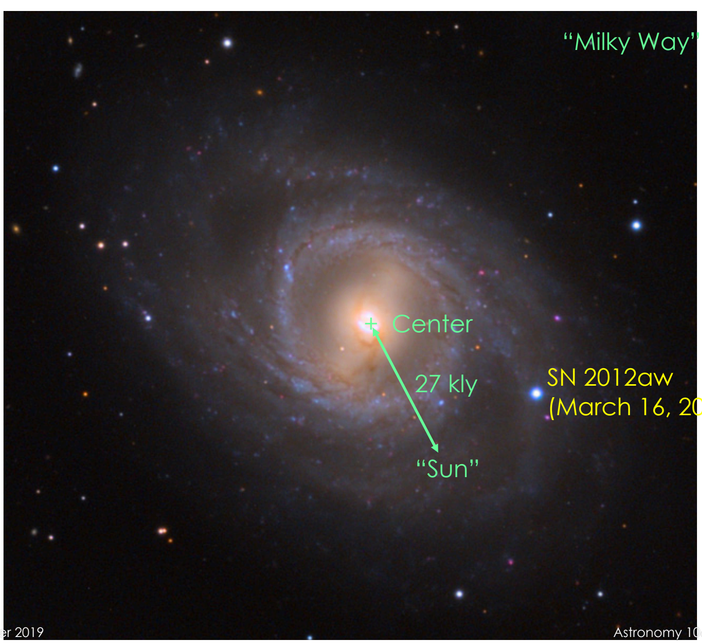

Adam Block, Mt. Lemmon SkyCenter, U. Arizona

How far to the next civilization?

The Sun lies $R = 27{,}000$ lyr = **27 klyr** from the Galactic center.

Most stars are closer to the center than the Sun.

We cannot actually view our galaxy from the outside, so we will use the nearby galaxy M95 as our working example, as it is quite similar to the Milky Way.

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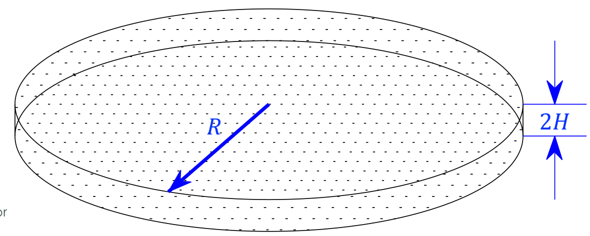
How far to the next civilization?

Suppose that you calculate a value for N and find that $N \gg 1$. How far apart are the civilization-hosting stars, as a rule?

To first approximation, let us assume that these N stars are uniformly distributed throughout the disk. (They are actually concentrated toward the center and the mid-plane.). Let us define n to be the number of stars per unit volume:

$$n = \frac{N}{V} = \frac{N}{\pi R^2 \times 2H}$$

The volume of space **per star** is $1/n$.



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How far to the next civilization?

If we imagine that each civilization-hosting star occupies an identical cubical volume with dimensions $r \times r \times r$ (where r is small compared to $2H$), then the centers of the cubes – and the planetary systems that they contain – are separated by that same distance r:

$$r^3 = \frac{1}{n} = \frac{2\pi R^2 H}{N} \quad \Rightarrow \quad \boxed{r = \left(\frac{2\pi R^2 H}{N}\right)^{\frac{1}{3}}}$$

Example: Take $R = 27$ klyr, $H = 330$ lyr, and $N = 3{\times}10^6$, as above:

$$r = 80 \text{ lyr}$$

r is indeed small compared to $2H$.

This tells us that a non-pessimist would say that communicable civilizations are typically close to 80 lyr apart.

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How far to the next civilization?

If, on the other hand, there are only a few civilizations, then their typical separation may be much larger than $2H$. We would then have to imagine that each star is confined to a box with dimensions $r \times r \times 2H$, for which:

$$2Hr^2 = \frac{1}{n} = \frac{2\pi R^2 H}{N} \quad \Longrightarrow \quad \boxed{r = R\sqrt{\frac{\pi}{N}}}$$

Example: Now use $N = 2$, with the other values the same as before:

$$r = 34 \text{ klyr}$$

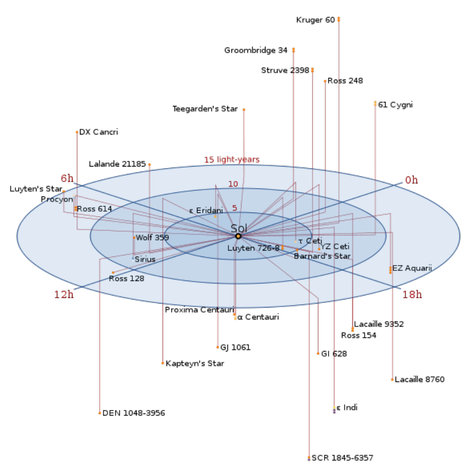
r is indeed large compared to $2H$ – a rather long way apart.

Finding & visiting other civilizations

The main issues:

- Most stars are far away. The closest system is the triple star α Centauri: $r = 4$ lyr.
- There are a lot of them, though: there are 20,000 stars within 50 lyr of us.
- Neither information nor astronauts can travel any faster than the speed of light:

$$c = 2.99792458 \times 10^{10} \text{ cm/s}$$
$$= 1 \text{ lyr/yr}$$



The 32 nearest stars

Finding & visiting other civilizations

At present, we cannot get astronauts to speeds anywhere near c; the fastest current spacecraft (NASA *New Horizons* / Pluto-Kuiper Express) cruises at 2.3×10^{6} cm/s $\approx 8\times10^{-5}c$.

So **the first thing to try is communication** rather than visits. As we will see, this is also considerably less expensive.

And until we find a civilization with which to communicate, we should both talk and listen…

…and account for the extreme delay between responses, on the scale of our usual attention spans. Even for relatively nearby civilizations, "conversations" would take many human lifetimes. (It would take 100 years just to say "Hi!" and receive a reply for a civilization only 50 lyr away.)

Communication with other civilizations

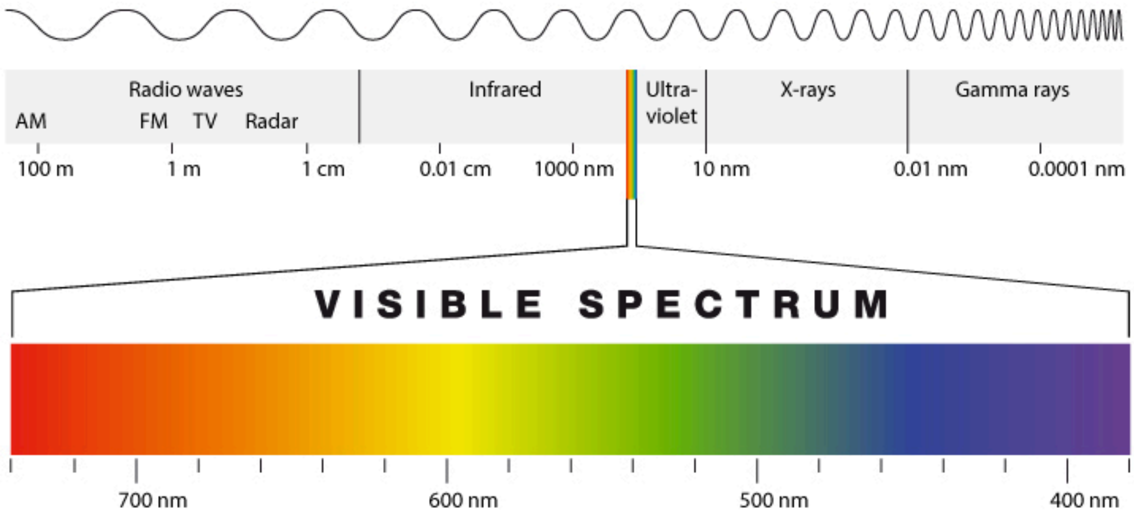
How would we communicate?

One thing seems clear: communication will involve **light**.

The precise wavelength of light at which the communication would be reasonable, though, is *not* naturally determined. The electromagnetic spectrum covers many orders of magnitude of wavelength, and a *signal* would cover a very small range of wavelengths around some central wavelength.

The electromagnetic spectrum (light)

Visible light is only a tiny part of the spectrum of light.



Communication with other civilizations

Issues which decide communication wavelength:

- Need to generate lots of broadcast power
- Need to broadcast that power in a narrow beam aimed at the specific stars. (It is wasteful to broadcast in all directions.)
- Need to detect and identify very small signals against natural backgrounds and noise.
- Need to avoid confusion with natural sources of light.
- Presuming at least some of the communications need to reach the surface of the habitable planets, the wavelength should be one at which the atmospheres are transparent.
- Our broadcast would probably attract more attention if it were near a wavelength of astrophysical significance, so that the astronomers of other civilizations have a higher probability of noticing it. Other civilizations might be thinking along these same lines as well.

Detection – the ideal frequency

We want to use a signal in the wavelength range that is most likely to be detected by other intelligent life-forms.

- On Earth, all life with sight has developed a sensitivity to **visible light**. (This is also the range in which our Sun is brightest; this is not a coincidence!)
- Our atmosphere is transparent to **radio frequencies**.

Stars shine very bright in the infrared and visible wavelengths.

To avoid our signal being drowned out by natural sources of electromagnetic radiation, the best option here is **radio** (assuming that other planets' atmospheres are also transparent in the radio).

Getting noticed

The 1-30 cm (radio) band is already largely free of strong local interference, since stars are not bright at these wavelengths, but it is still a lot of wavelength space to cover.

Special locations that astronomers would notice the signal:

- **The water hole**. Two of the brightest spectral lines from interstellar gas, the 21 cm line of atomic hydrogen (H) and the 18 cm lines of hydroxyl (OH), would undoubtedly attract the attention of extraterrestrial astronomers. Frank Drake and Carl Sagan used to draw attention to the gap between them as a result. (H + OH = water)
- **The real water hole**. Bright, natural maser emission from water itself at 1.3 cm, would certainly attract attention.

But there are zillions of important spectral lines in the band.

The broadcast itself

We cannot just send a steady wave at a given wavelength – we must **modulate** the wave so that a stream of information at longer wavelengths / lower frequencies is obtained by removing the steady **carrier**. This is how all optical and radio transmission works.

- In radio, the carrier is modulated at audio – voice – frequencies.
- AM and FM refer to the methods of modulation common in radio.

We also need to broadcast a **primer**: something that could help de-cypher our modulations.

- This is best if it is related to natural or mathematical concepts, like prime numbers or the periodic table.

What do we look for?

Artificial signals pulse with a constant frequency, while natural signals normally vary in their modulations.

- Pulsars (fast-spinning neutron stars) were originally named "Little Green Men" because no natural emission mechanism could be imagined at the time to produce such a regular pulse.
- Such natural occurrences of regular pulsation are extremely rare.

The most difficult signal to filter out is our own.

- If an alien's signal had a period matching one of our units of time (second, minute, etc.), then we would probably miss it because we would assume it had a terrestrial origin.

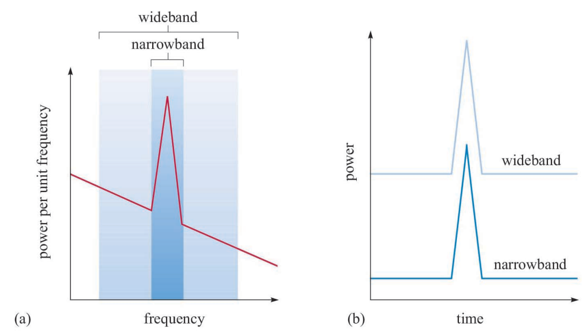
The signal’s bandwidth

Wideband – Spread the total energy in the signal out over a wide range of frequencies

- Advantage: Receiver tuning is less crucial
- Disadvantage: Signal is not as strong relative to the background

Narrowband – Concentrate the total energy of the signal in a narrow range of frequencies

- Advantage: Signal is very strong
- Disadvantage: Easy to miss if receiver is not looking at the exact signal frequency



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Question!

An alien transmits at 1420 MHz (21 cm) with a bandwidth of 10 Hz. Which bandwidth do you select on a radio telescope which can be set to monitor a channel at this frequency to be able to detect the largest signal relative to the background?

A. 1 Hz
B. 5 Hz
C. 100 Hz

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Where to look?

This depends on whether we want to detect intentional or unintentional transmissions.

- **Unintentional transmissions** – Random EM radiation broadcast from a distant civilization
  - Very weak, since they would be spread out in many directions (unfocused)
  - Limited to the nearest star systems (small number of targets to check!)
  - Covers a broad range of frequencies / wavelengths
- **Intentional transmissions** – EM radiation sent as an advertisement
  - Strong signal, since the beam would be pointed directly at us
  - Can see much further away (long list of targets)
  - Very narrow frequency / wavelength coverage

Searching for intentional transmissions is much more time-consuming, but the potential for a conversation is much higher.

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From how far away would we notice ourselves?

The Arecibo 305-m radio/radar telescope can broadcast about 2 MW at 2.4 GHz, which is equivalent to broadcasting about 20 TW (trillions of watts) in all directions (to those at which the signal is pointed).

This is presuming the sensitivity on the previous page, and presuming a simple message.

Averaging that message for a period of 8 hours, we would adequately detect our own message from a distance of about **50 lyr**.

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Symbol	Value	Meaning
π	3.14159…	Ratio of a circle's circumference to its diameter
e	2.71828…	Euler's number, used in exponential function and natural logarithms
1,2,3,5,7,11,13,…		Prime numbers
1,2,3,8,16,32,64,…		Powers of 2
0,1,1,2,3,5,8,13,…		Fibonacci sequence ($F_n = F_{n-1} + F_{n-2}$)
c	3×10^{8} m/s	Speed of electromagnetic radiation in a vacuum
m_e	9×10^{-31} kg	Mass of the electron
m_p	1×10^{-27} kg	Mass of the proton
76/24 = 3.17		Mass ratio of hydrogen to helium in early Universe
$M_\odot$	2×10^{30} kg	Mass of the Sun

With what do we communicate?

Despite not knowing anything about the other intelligent life forms, if we can communicate via radio waves, then we must share some **common knowledge**.

Any quantity whose value depends on the units is problematic.

How do we send these numbers?

Whatever information we want to communicate to another civilization to break through the language barrier must be somehow **encoded** in the radio signal pulses that we send.

- The most natural number system we have on Earth is the **binary** system: 1 or 0 (on or off, yes or no, nothing or something).

The only issue that remains is to hope that the other civilization reads the sequence of 1s and 0s from left to right (the order in which we encode the signal). If they read from right to left, hopefully they will realize that the translation does not make sense and try it the other way.

So, we need to look for general signs of structure in messages from other systems instead of searching for particular numbers.

The search for extraterrestrial life

SETI is thus proceeding through targeted broadcasts and searches (mostly the latter) at radio frequencies. This is the main effort of the SETI Institute, the professional home of Frank Drake and Jill Tarter.

Most notable: observations with the Arecibo 305-m telescope in the direction of 800 sunlike stars with $r < 200$ lyr, 1998-2004.

Search through the data for signals by a vast array of PCs in the hands of amateurs: SETI@Home

No detections yet. We would have definitely heard about it if there had been.

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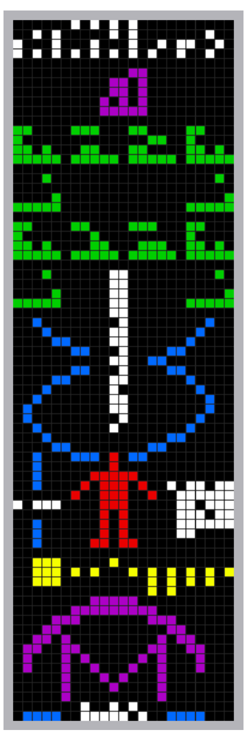

Numbers 1-10

Atomic numbers of H, C, N, O, P

Formulae for sugars and bases in DNA nucleotides

Number of nucleotides in DNA

Double helix of DNA

Human being
Height of human being
Human population of Earth

Solar system

Arecibo telescope transmitting message
Diameter of the telescope

Our first message

Sent in binary from Arecibo in 1974 by Drake.

There are 1679 bits in the message. 1679 is divisible by only two numbers (besides itself and 1): 23 & 73. These indicate the dimensions of the image.

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SETI

Additional searches are conducted with other radio observatories to exploit wavelengths or parts of the sky inaccessible to Arecibo:

- The Karl G. Jansky Very Large Array (VLA) in New Mexico, a 27-element array of 26-m telescopes acting as a single telescope many km across.
- The Robert C. Byrd Green Bank Telescope (GBT), a 100-m diameter fully steerable radio telescope in West Virginia.
- The Five-hundred-meter Aperture Spherical Radio Telescope (FAST), a 500-m diameter dish constructed in a natural basin (the Dawodang depression) in southwest China.

VLA in its most compact configuration

GBT

FAST

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SETI

- The Allen Telescope Array in Hat Creek, CA. This is envisioned as a 350-element array of 6-m diameter radio telescopes, of which 42 are currently operating.
- Arecibo is still one of the most powerful tools for SETI: it has 5 times the collecting area of the VLA.
- But the Square Kilometer Array (SKA), to be completed by 2025, will have 15 times the collecting area of Arecibo and could detect our civilization from a distance of **200 lyr**.

Part of the ATA

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SETI

We are currently decently equipped to detect extraterrestrial signals at radio wavelengths, though the effort is traditionally underfunded and little appreciated.

Although the culture of radio astronomy is changing, most of the depiction of SETI in the movie *Contact* still applies: PhD thesis advisors do not like to see their students going into SETI.

The ongoing search for extrasolar planets – especially projects like NASA's *Kepler*, *K2*, and TESS, which search for habitable planets – will provide more and better targets to which to broadcast, and toward which to search for signals.

And sensitivity, bandwidth, and analysis power will continue to improve.