Ends of the World are coming

Overview

What is exactly the End of the World?

Any natural phenomenon which

- Causes a mass extinction
  - Asteroid impacts
  - Supernovae explosions
  - Gamma ray bursts
- Makes Earth permanently inhospitable to life
  - End of the habitable zone
- Physically destroys Earth
  - Red giant stage of the stellar evolution

City killers

- An object with $D < 10\mathrm{m}$ vaporizes in the atmosphere
- Rocks with a diameter 20 – 100 m hit the surface.

Is it really that bad?

- $\rho \sim 3000\,\mathrm{kg/m^3}$ (granite)
- $v \sim 30 - 80\,\mathrm{km/sec}$ (typical speed of Solar system objects)

$E = \frac{mv^2}{2} = \frac{2}{3}\pi\rho R^3 v^2 \sim 10\,\mathrm{MT}$, where $1\,\mathrm{MT} = 4.18 \cdot 10^{15}\mathrm{J}$.

This happens roughly once a century

- 2013 Chelyabinsk meteor
- 1908 Tunguska event

Massive killing capacity

Diameter $\sim 500\,\mathrm{m}$ (once in ~ 50000 years)

- Similar to detonating the global nuclear arsenal at once
- Enough devastate a whole continent

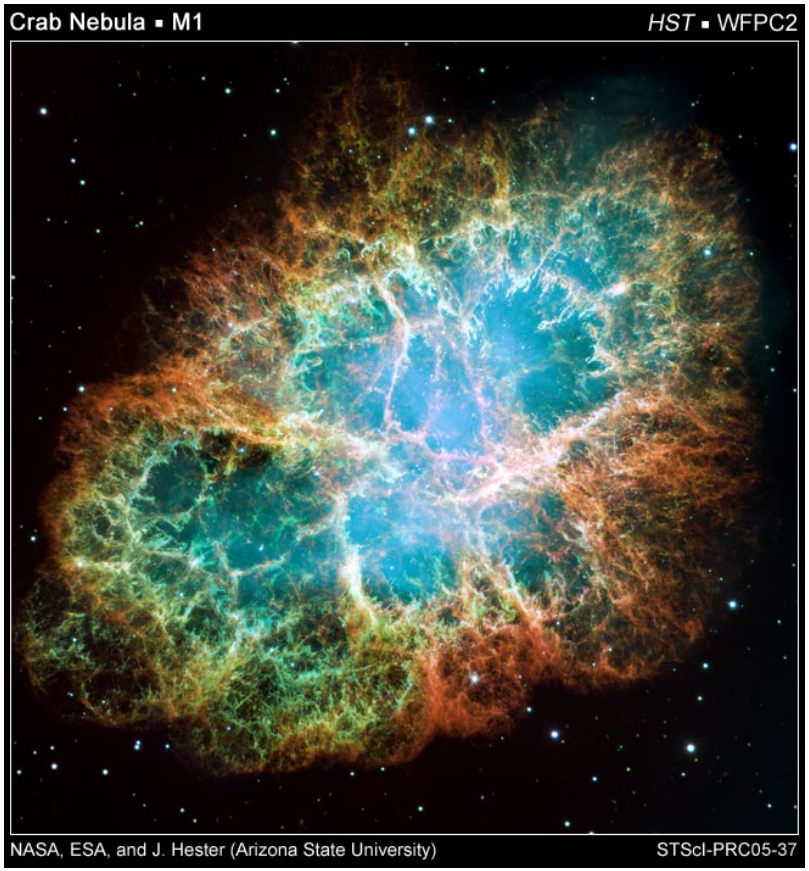
Diameter 2 – 3 km (once a couple of million years)

- Ejects and disperses lots of material
- It stays in the atmosphere for years and causes a global cooling

Diameter 5 – 10 km (roughly once in 100 million years)

- Nuclear winter lasts decades, oceans get acidified
- Presumably caused the Cretaceous-Paleogene extinction (poor dinosaurs)

Supernova explosions



- Heavy stars ($M > 8M_{\odot}$) collapse at the end of the lifetime
- Collapse causes a huge thermonuclear explosion
- During a few weeks supernova outshines a whole galaxy
- Supernovae occur once a 50 years in a galaxy of Milky Way size

Supernova explosions

- Explosion sprays EM radiation and ultra-relativistic particles
- Life on a planet closer than 50 – 100 LY is in a trouble
- There are no dangerous stars at such distances for now
- In the future the Sun might move to a less cozy place

Gamma ray bursts

Supernova explosions of rapidly rotating stars

- Powerful magnetic fields form during the collapse
- Magnetic fields focus the explosion products
- Narrow streams might be deadly even at $\sim$ 10000 LY

Other causes

- Neutron stars mergers
- Black holes mergers

GRB safety notice

Do I need to run to a radiation shelter?

1. It's too late (most GRB are seconds to minutes long)
2. Most of GRB radiation gets blocked by the atmosphere

Any dangerous stars around?

Perhaps WR 104 in 8000 LY

How often GRBs happen close enough to Earth?

A rough estimate: once in 1 Gyr

Why exactly GRBs are harmful?

Global cooling

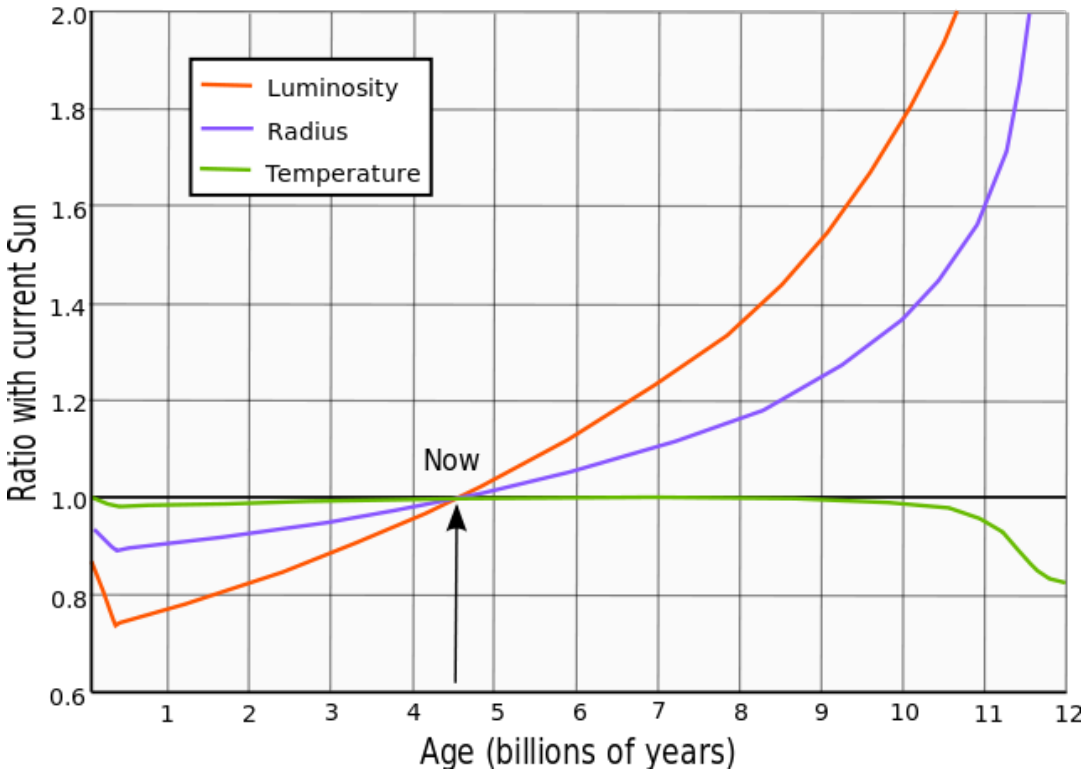
- Gamma rays break N_2 and O_2 molecules into atoms
- Which recombine into nitrogen oxides NO, NO_2
- These molecules can float in the stratosphere for years
- NO_2 efficiently blocks the visible light

Mass extinction due to increased UV level

- NO destroys ozone: $NO + O_3 \rightarrow NO_2 + O_2$
- Solar UV level at the Earth surface increases
- 30% solar UV increase is enough to kill phytoplankton

Ordovician-Silurian mass extinction (44O Myr ago) might have been caused by an GRB [1]

Sun evolution at the main sequence



Evolution of the Solar luminosity, radius, and temperature [2]

Consequences for life on Earth

- Photosynthesis shutdown in 800 Myr
- Loss of oceans in 1 Gyr
- Extinction of the remaining life forms in 2.8 Gyr

Photosynthesis shutdown

Rocks slowly convert atmospheric CO_2 into carbonate minerals:

$$CaSiO_3 + CO_2 + H_2O \rightarrow 2HCO_3^- + Ca^{2+} + SiO_2$$

- The rate rapidly increases with the temperature
- In 600 Myr CO_2 concentration will be 50 PPM [3] versus the current 400 PPM
- 50 PPM is too low for C_3 carbon fixation
- Vast majority of plants use C_3 process, these will die (including all trees)
- Plants relying on C_4 carbon fixation will follow in 200 Myr

Loss of oceans

- A 10% increase of the solar luminosity bumps the global surface temperature to 320 K (47°C)
- The atmosphere will become a "moist greenhouse" leading to runaway evaporation of oceans [5]
- The stratosphere will contain increasing levels of water
- Solar ultraviolet will break water molecules into oxygen and hydrogen
- Light hydrogen molecules easily escape to the space
- Net result: loss of all ocean water in 1 Gyr

Note: oceans don't need to boil for this to happen

Extinction of the remaining life forms

- There will be several oceans worth of water in the mantle [4]
- Lots of microbes will definitely move and adapt
- In 2.8 Gyr from now: $T_{surface} = 422\,\mathrm{K}$ $(149^{\circ}\mathrm{C})$
- All life forms will be extinguished due to extreme conditions
- Remaining water might cause further runaway moist greenhouse effect
- The surface temperature will raise to 1600 K (enough to melt the surface)

Milky Way and Andromeda

Milky Way and Andromeda now

Milky Way and Andromeda

Milky Way and Andromeda in $\sim$ 3.5 Gyr from now

Milky Way and Andromeda merger

- Andromeda is approaching us at $\sim 110\,\mathrm{km/sec}$.
- That's not enough for collision: the transverse speed matters.
- According to recent measurements by Hubble space telescope [6] and Gaia mission [7] Andromeda will definitely hit us.
- ETA: 3.75 – 4.5 billion years.
- Stellar collisions are extremely unlikely: $D(\alpha Cen - \odot) \sim 3 \cdot 10^7 D_\odot$

Super massive black holes merger

- A super massive black hole (SMBH) of $3.6 \cdot 10^6 M_\odot$ resides at the center of Milky Way
- A SMBH of $1 - 2 \cdot 10^8 M_\odot$ resides at the center of Andromeda
- They will converge near the center of the newly formed galaxy and merge
- Nearby ordinary stars will be slingshotted to higher radius orbits or ejected from the galaxy
- Gas clouds attracted by SMBHs could create a quasar ($\sim 10^7$ supernova explosions)
- Stars passing too close to SMBH can be torn apart by the tidal force

Burst of star formation

- Gas clouds collide and compress, and form new stars
- The Sun can acquire heavy neighbors which can go supernova in a couple of million years
- At that time Earth would be lifeless anyway

Further Ends of the World

- Sun goes red giant and expands beyond the current Earth orbit, ETA: 5 Gyr
- Accelerated expansion of space-time drags all galaxies beyond the cosmological horizon, ETA: 600 Gyr
- Last (red dwarf) star dies, ETA: 100 Tyr
- Planetary system dissolved by close encounters between stellar remnants, ETA: 10^{15} yr
- Galaxies dissolution: heavier bodies fall to the center, and lighter fling into the void, ETA: 10^{18} yr
- Last black hole evaporates, ETA: 10^{100} yr

Quantum fluctuations may spawn new Universes

ETA: $10^{10^{10^{\cdots}}}$

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