# 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 $\sim 50000$ 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)

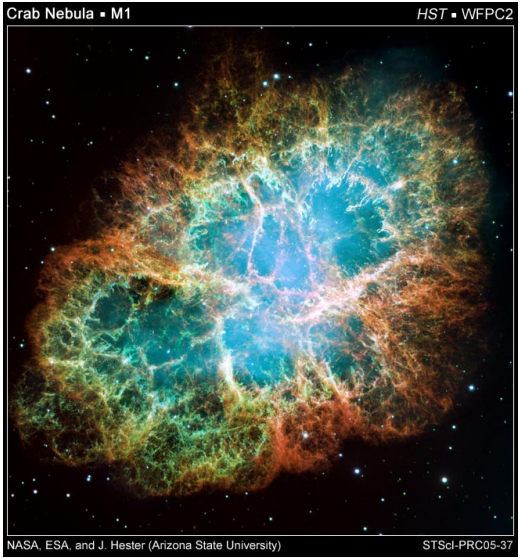
# Supernovae explosions

- 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
- Explosion sprays EM radiation and ultra-relativistic particles
- Life on a planet closer than 50 – 100 LY is in a trouble

## This will never happen to me

- Supernovae occur once a 50 years in a galaxy of Milky Way size
- There are no dangerous stars at such distances for now
- In the future the Sun might move to a less cozy place

# Supernovae explosions




- $\approx 11\,\mathrm{ly}$ across
- $\approx 6500\,\mathrm{ly}$ away
- Described by chinese astronomers circa 1054
- Was bright enough to be seen in the daytime

# 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

## Don't do this at home!

GRB 221009A: $E_{iso} \sim 6.5 \times M_{\odot} \approx 1.2 \times 10^{47}\mathrm{J} \approx 3.5 \times 10^{32}\mathrm{MT}$ [2]

## 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

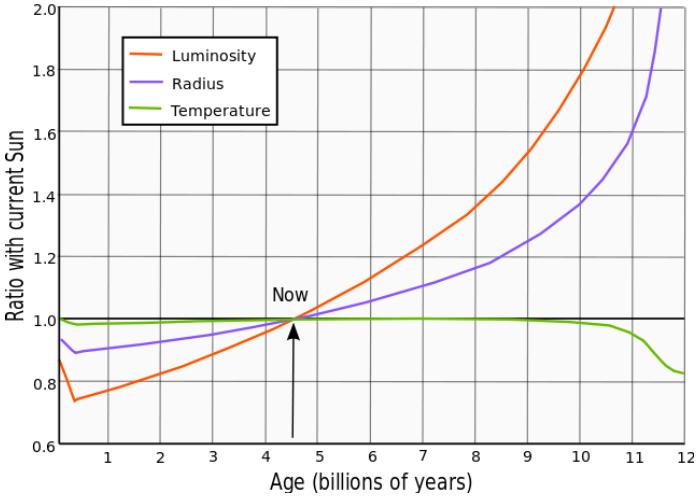
- Gamma rays break $N_2$ and $O_2$ molecules into atoms
- Which recombine into nitrogen oxides $NO$, $NO_2$
- These molecules can float in the stratosphere for years
- $NO_2$ efficiently blocks the visible light

## 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

Possible cause of Ordovician-Silurian mass extinction (44O Myr ago) [1]

# Sun evolution at the main sequence




Evolution of the Solar luminosity, radius, and temperature [3]

# Shine on you crazy diamond

## Gravity versus nuclear synthesis

- Hydrogen in the core gets diluted, fusion slows down temporarily
- Core shrinks, pressure increases (same mass above, smaller surface)
- Fusion rate increases and balances the increased crush

## Stars brighten as they deplete their hydrogen fuel

- Over time core shrinks and heat up
- Outer layers slightly expand
- Sun becames 1% brighter every 100 Myr

## 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

## Basalt

- Most common volcanic rock on Earth
- 47 – 52% $SiO_2$, 14 – 18 % $Al_2O_3$, **6 – 12 %** CaO

Atmospheric $CO_2$ slowly converted into carbonate minerals:

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

- The rate rapidly increases with the temperature
- $CO_2$ concentration in 600 Myr: 50 PPM [4] (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 [6]
- 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 [5]
- 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

now

# 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 [7] and Gaia mission [8] 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: $10^{10^{10^{\cdots}}}$

A. Melott, B. Lieberman, C. Laird, L. Martin, M. Medvedev, B. Thomas (University of Kansas), J. Cannizzo, N. Gehrels, C. Jackman (NASA-Goddard)

Did a gamma-ray burst initiate the late Ordovician mass extinction?

astro-ph/0309415

D. Frederiks, D. Svinkin, A. L. Lysenko, S. Molkov, A. Tsvetkova, M. Ulanov, A. Ridnaia, A. A. Lutovinov, I. Lapshov, A. Tkachenko, V. Levin

Properties of the extremely energetic GRB 221009A from Konus-*WIND* and *SRG*/ART-XC observations

arXiv:2302.13383

I. Ribas (2009)

The Sun and stars as the primary energy input in planetary atmospheres

arXiv:0911.4872

Martin J. Heath, Laurance R. Doyle

Circumstellar Habitable Zones to Ecodynamic Domains: A Preliminary Review and Suggested Future Directions

arXiv:0912.2482

Bounama, C., Franck, S., and von Bloh, W. (2001)
The fate of Earth's ocean
Hydrol. Earth Syst. Sci., 5, 569-576

Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus
Icarus (ISSN 0019-1035), vol. 74, June 1988, p. 472-494.

Roeland P. van der Marel, Mark Fardal, Gurtina Besla, Rachael L. Beaton, Sangmo Tony Sohn, Jay Anderson, Tom Brown, Puragra Guhathakurta
The M31 Velocity Vector. II. Radial Orbit Towards the Milky Way and Implied Local Group Mass
arXiv:1205.6864

Roeland P. van der Marel, Mark A. Fardal, Sangmo Tony Sohn, Ekta Patel, Gurtina Besla, Andrés del Pino-Molina, Johannes Sahlmann, Laura L. Watkins
First Gaia Dynamics of the Andromeda System: DR2 Proper Motions, Orbits, and Rotation of M31 and M33
arXiv:1805.04079