FLORIDA TECH

The Impact of Gamma-Ray Bursts on Cometary Systems

Could a nearby GRB trigger a cometary bombardment?

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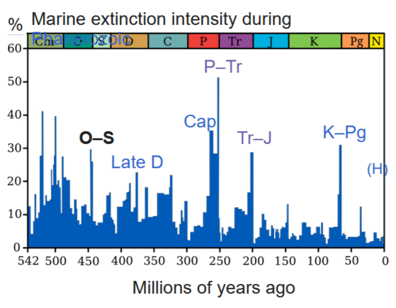
Abstract

Many studies have examined the effects of a gamma-ray burst (GRB) on the atmospheres of habitable planets. But a planetary system will also contain asteroids, comets, and other minor bodies. We examine the interaction of a nearby GRB on these minor bodies, such as changes to orbital parameters. For example, could a GRB cause a period of cometary bombardment by destabilizing orbits?

ChatGPT/Dall-E 3 image with the prompt "gamma ray burst happening behind an Oort cloud". This is the only use of AI in this poster.

Background

- GRBs at cosmological distances have measurably affected Earth's atmosphere. [1, 2]
- A closer GRB would produce enough γ-ray flux to damage Earth's ozone layer, harming life on Earth
- A GRB may have caused the Ordovician mass extinction, 445 million years ago [3]



- Damage to ozone layer dependent on γ-ray fluence

Fluence (kJ/m²)	Ozone loss (%)	D_{GRB} (kpc)	Quality
10	64	9	"Some damage to life"
100	91	3	"Life threatening"
1000	98	1	"Catastrophic"

Ozone loss from [4]. D_{GRB} assumes L_γ = 10^{52} erg/s, Δt = 10 s. Quality from [5].

- Solar System is surrounded by spherical Oort Cloud extending to 100,000 AU [6]
- Estimated 10^{12} objects of 1 km radius with semi-major axis a > 20,000 AU [6]
- Such objects only loosely bound to Sun, and easily perturbed by passing stars—or by GRBs?
- A GRB may provide sufficient fluence to destabilize distant orbits without severely impacting Earth's ozone layer

[1] Fishman & Inan (1988), 1988Natur.331..418F
[2] Hayes & Gallagher (2022), 2022RNAAS...6..222H
[3] Melott et al. (2004), 2004IJAsB...3...55M
[4] Thomas et al. (2005), 2005ApJ...634..509T
[5] Piran & Jimenez (2014), 2014PhRvL.113w1102P
[6] Wiegert & Tremaine (1999), 1999Icar..137...84W

Key equations

$$\varepsilon_{\rm orb} = -\frac{GM_\odot}{2a}$$

- Mechanical energy per unit mass [J/kg] of object in circular orbit distance a from Sun

$$\Delta\varepsilon = \frac{3\mathcal{F}}{4\rho R}$$

- Change in specific energy: absorbed γ-ray energy ($\pi R^2 \mathcal{F}$) divided by object mass ($\frac{4}{3}\pi R^3$)

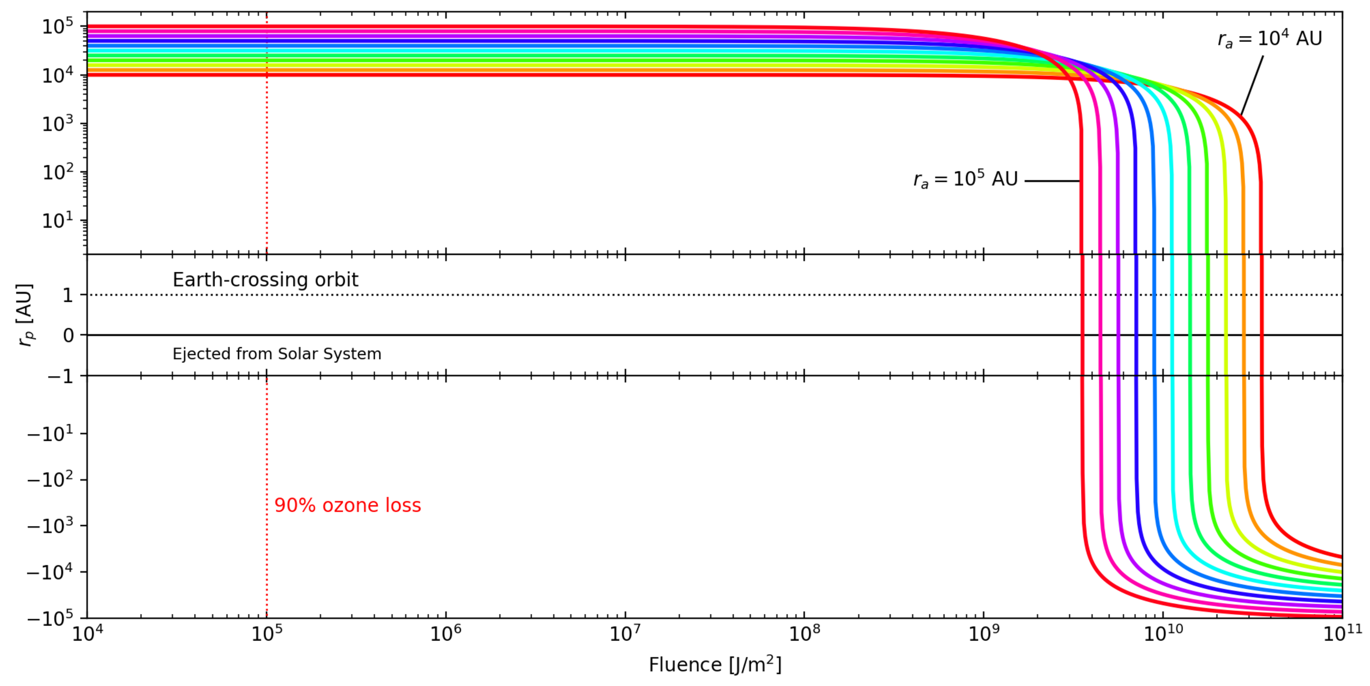
$$\frac{r_{p,\rm new}}{a} = \frac{GM_\odot - 2a\Delta\varepsilon}{GM_\odot + 2a\Delta\varepsilon}$$

- Ratio of new orbit's perihelion to old orbit's radius
- For $r_{p,\rm new}$ < 1 AU (Earth-crossing orbit) and $a \gg 1$ AU, need $GM_\odot \approx 2a\Delta\varepsilon$
- If $GM_\odot < 2a\Delta\varepsilon$, object unbound & ejected into galaxy (like 'Oumuamua & Borisov)

Results

Fiducial model:

- ρ = 600 kg m^{-3} ("dirty snowball")
- R = 1 km
- a = 100,000 AU



Any GRB that would destabilize our fiducial comet would sterilize Earth.

So, Earth is safe from GRB-induced cometary bombardment.

What about other systems? First, difference between $r_{p,\rm new}$ = 1 AU and $r_{p,\rm new}$ = 0 (i.e. ejected from stellar system) negligible. With $r_{p,\rm new}$ = 0, critical fluence given by

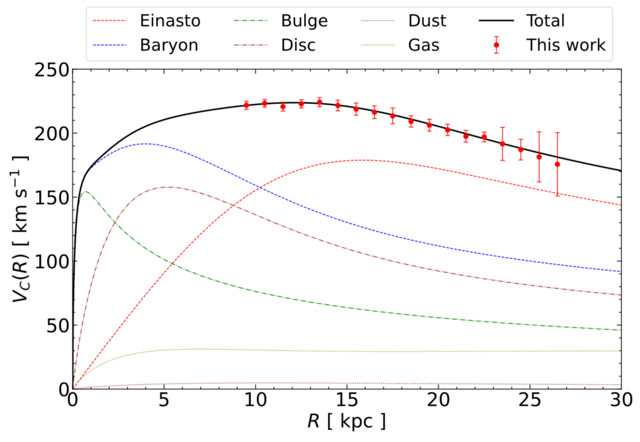
$$\mathcal{F}_{\rm crit} = \frac{2\rho R G M_\star}{3 r_a}$$

Radius of Oort cloud (r_a for other system) defined by star's sphere of influence within galaxy potential. For star of mass $M_\star$ orbiting distance D from galaxy center, need to know total mass contained within orbit.

$$\frac{r_{\rm SoI}}{D} = \left(\frac{M_\star}{M(<D)}\right)^{2/5}$$

$M(<D)$ found from galaxy rotation curves: $v_{\rm circ}^2 = G\,M(<D)/D$

Jiang et al. (2023), 2023A&A...678A.208J



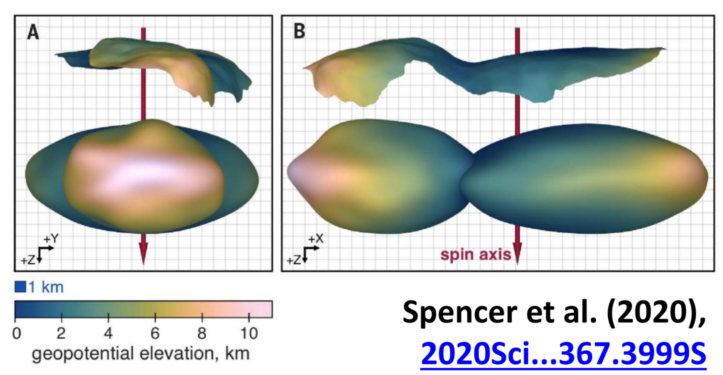
Putting everything together, then,

$$\mathcal{F}_{\rm crit} = \frac{2\rho R\,(GM_\star)^{3/5}\,v_{\rm circ}^{4/5}}{3\,D^{3/5}}$$

Most exoplanet systems, in any galaxy, will be safe from bombardment.

- $\mathcal{F} \propto M_\star^{3/5}$: changing from Sun to M-type dwarf ($M_\star$ = 0.1 $M_\odot$) reduces critical fluence by only factor of 4
- Dependence on galactic potential even weaker. Low-mass dwarf galaxies with small $v_{\rm circ}$ also smaller, reducing D (Sun's $v_{\rm circ}$ = 220 km/s at D = 8 kpc from galactic center; orbits in Large Magellanic Cloud have $v_{\rm circ} \approx$ 70 km/s, but $D \sim$ 4 kpc)

Even asymmetric cometary bodies, such as Arrokoth, won't change $\Delta\varepsilon$ by more than an order of magnitude



Spencer et al. (2020), 2020Sci...367.3999S

Conclusion

Any gamma-ray burst close enough to trigger a cometary bombardment would also be close enough to harm the habitability of Earth (or of any exoplanet) via the conventional method of destroying the ozone layer.

Next steps

A continued examination of the interaction between GRBs and habitability on Earth (or exoplanets).

1. Traditionally [5], a single luminosity is used for computing GRB impact on Earth. Is conclusion changed by using full population of $E_{\rm iso}$ and $E_{\rm pk}$?
2. GRB afterglow lasts longer and is visible at wider angles than prompt emission. Does long-term, weak forcing of ozone layer impact habitability?