Astrophysical Events as Episodic Threats to Life on Earth

Brian C. Thomas
Dept. of Physics and Astronomy
Washburn University

Work supported by NASA grant No. NNX09AM85G
Astrophysical Radiation & Earth

• High energy radiation:
  – X-rays, gamma-rays
  – Cosmic rays – charged particles (protons)

• Effects:
  – Atmospheric chemistry changes
    • Nitrogen dioxide “smog”
    • Stratospheric Ozone depletion
  – High-E CRs => energetic muons
    • Muons are highly penetrating
Long-Term Consequences

- Life at the surface sees enhanced UV for years
  - UV strongly affects DNA, proteins, etc.
  - Phytoplankton and other surface dwellers hit hardest
  - Food-web impact
  - Mass Extinction?

O₃ depletion, latitude v. time

Cooling due to opacity of NO₂?

New Scientist, Sept. 2003

A Range of Sources

In order of *increasing* energy and *decreasing* frequency:

- **Solar proton events (CMEs)**
  - Primarily protons
  - Up to $10^{25}$ Joules total

- **Supernovae** (various types)
  - X- and gamma-ray photons
  - CRs (partly location dependent)
  - Up to $10^{46}$ Joules
  - Important at 10’s of light years

- **Gamma-Ray Bursts** (2 types)
  - X- and gamma-ray photons
  - Up to $10^{47}$ Joules
  - Important at 1000’s of light years
Supernova

• Photons for ~ 1 year
  – Global average O$_3$ depletion up to 35%, lasting up to a decade (assuming distance of ~ 30 light years)

• Cosmic ray enhancement ~ thousand years
  – Also causes O$_3$ depletion
  – High energy CRs => penetrating muons

• Iron-60 detections around 2.5 Ma strongly indicate a SN at maybe 150 light years.
Gamma-Ray Bursts

- Two main types, both strongly beamed.
  - Long-soft GRB
    - Duration: > 2 s (typical ~ 10 s)
    - Softer spectrum (lower peak photon energy)
    - Special case of core-collapse SN (?)
  - Short-hard GRB
    - Duration: < 2 s (typical ~ 0.1 s)
    - Harder spectrum (higher peak photon energy)
    - Compact-object merger (?)
Rates for “significant” events

- Rate vs. Fluence (energy per unit area)
  - Fluence convolves total energy and distance
- Solar, SN, Short-Hard GRBs, Long-Soft GRBs
- $O_3$ global average depletion thresholds:
  - 1) ~5%: current, 1859 SPE
    - noticeable bio effect
  - 2) ~35%: 100 kJ m$^{-2}$ fluence (GRB, SN)
    - major bio impact – mass extinction?
Event Intervals

- Rates summed over all event types.
- Dominated by:
  - Solar at low fluence
  - Supernova and short-hard gamma-ray burst at high fluence
Estimated Rates

• For events that yield ~ 35% globally averaged O₃ depletion:
  – Short-Hard GRBs: 1 per 300 million years
  – Supernovae: 1 per 500 million years
  – Long-Soft GRBs: 1 per billion years

• For events that yield ~ 5% globally averaged O₃ depletion:
  – Solar: 1 per 1000 years?*
    • Uncertain, few data points, extrasolar data support
  – Supernovae: 1 per 1 million years
  – Short-Hard GRBs: 1 per 3 million years
  – Long-Soft GRBs: 1 per 30 million years

* See Melott & Thomas, Nature, 2012; Thomas et al., GRL, 2013
Extinctions

- 35% global O$_3$ depletion expected to have severe impact for several years.
- We have previously identified correlations in late Ordovician extinction:
  - Depth and latitude dependence (Melott et al. 2004, Thomas et al. 2005, Melott & Thomas 2009)
- Work in progress to better quantify impact on marine primary producers.
- Future work investigating ecological impact?
End-Ordovician Extinction

- Unexplained short period of glaciation ($\text{NO}_2$ cooling?)
- Bias toward extinction of shallow water organisms, surface dwellers…
- Computed DNA damage from a group of simulations for a variety of southern hemisphere GRB cases
- Data points are extinction rates as a function of latitude.
  - Krug & Patzkowsky, 2004, PNAS
- GRB over the (paleo) South Pole fits

From Melott & Thomas, Paleobiology 35, 311 (2009).
Resources and Acknowledgements

• “Astrophysical Ionizing Radiation and Earth: A Brief Review and Census of Intermittent Intense Sources”
  – Melott & Thomas, Astrobiology, v.11 (2011)
• “Late Ordovician geographic patterns of extinction compared with simulations of astrophysical ionizing radiation damage”
• “Gamma-Ray Bursts as a Threat to Life on Earth”
• “Causes of an AD 774-775 $^{14}$C increase”
• “Terrestrial effects of possible astrophysical sources of an AD 774-775 increase in $^{14}$C production”

Pre-prints available at arXiv.org
Thanks to various collaborators and students!
Current work supported by NASA grant No. NNX09AM85G
END
Summed Rate vs. Fluence

- Dominated by:
  - Solar at low fluence
  - Supernova and short-hard gamma-ray burst at high fluence

SN:
From D^{-2} to D^{-3}
Inside remnant
Varying Event “Hardness” in Photons

- Same total energy received.
- Vary the relative number of high energy photons.
- Broadly, Harder = worse

Globally averaged column O$_3$ change

Varying Event Duration

- Constant spectrum and energy received.
- Duration from $0.1 \text{ to } 10^8 \text{ s}$
- Broadly,
  - Variation in timing
  - But, similar total depletion

Rate vs. Fluence

- Solar: Line, Recent SPE; Dots, historical SPE
- “Moon” upper limits on cumulative exposure rates from lunar radionuclides ($x=\text{goal}$; isotopes, ice cores)
- SN
- SHGRB
- LSGRB

SN: From $D^{-2}$ to $D^{-3}$ Inside remnant

![Graph showing log rate per year vs. log fluence (J/m^2)]
Atmo Effects: 1859 Flare

• O₃ depletion:
  – Max 5% global avg.
  – Similar to current
  – Recovery ~ 4 yrs

Thomas et al. 2007, GRL, 34, L06810
Atmo Effects: Long GRB

- Location and season of burst affect intensity and geographic distribution of impact.
- Globally averaged depletions up to 35%
Solar UV and Biological Effects

- **Surface UVB (280-315 nm)**
  - Solar UVB attenuated by \( \text{O}_3 \) column
  - Simple approach (no scattering, etc.)
- **DNA damage**
  - Computed using a *weighting function* (Setlow 1976) and solar UVB irradiance.
Relative DNA damage (normalized by annual global average pre-burst)

Note primarily mid-low latitudes affected.
Did a GRB initiate the Late Ordovician Mass Extinction?

~ 440 million years ago
2nd largest mass extinction known

Primarily shallow-sea life at this time.
No known land life.

We first proposed this connection in 2004 in IJA

http://pubs.usgs.gov/gip/fossils/numeric.html

Courtesy W. Berry, UC Museum of Paleontology
<table>
<thead>
<tr>
<th>Predicted GRB Effects</th>
<th>Late Ordovician Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extinction of shallow (not deep) water organisms !</td>
<td>Yes (correlation)</td>
</tr>
<tr>
<td>Extinction of free-swimming organisms !</td>
<td>Yes (correlation)</td>
</tr>
<tr>
<td>Extinction of surface floaters plankton/planktonic larval forms !</td>
<td>Yes (correlation)</td>
</tr>
<tr>
<td>Nitric acid rain ?</td>
<td>Productivity oscillation in biosphere possibly related to nitrate boost.</td>
</tr>
<tr>
<td>Reduction of solar radiation – cooling ?</td>
<td>Yes – glaciation needed “kick”</td>
</tr>
<tr>
<td>Extinctions begin with GRB !</td>
<td>Extinctions preceeded glaciation and began with plankton</td>
</tr>
<tr>
<td>No iridium layer due to asteroid, no $^{244}$Pu residue from nearby supernova</td>
<td>Unknown (not yet observed)</td>
</tr>
</tbody>
</table>

Can we predict any other effects, test the idea in additional ways?
Is this a falsifiable hypothesis?
Latitude dependence of extinction

- Krug and Patzkowsky (2007) analyzed the pattern of extinction in the Ordovician.
  - Presented extinction intensities on three continents, varying in latitude.

- Our simulations show a pattern of damage as a function of latitude. Can now test the hypothesis:
  - If UV effects were a dominant part of the extinction, we should be able to match their pattern.

- Any GRB had to be southern hemisphere
  - Fossil record documents a southern hemisphere extinction
  - Atmospheric effects typically are confined to northern or southern hemisphere.
Extinction Intensity Patterns

• All cases show a maximum damage intensity at a latitude that depends on burst latitude.

• Scale shows: maximum damage intensities for southern hemisphere bursts normalized to average value of maxima at equator for all cases.
Comparison with Ordovician Data

• Diamonds (with 2σ error bars) represent sampling-standardized extinction intensities from Krug and Patzkowsky (2007)
• Lines correspond to bursts at latitude 0°, -45°, -60°, and over the South Pole -90° (max damage normalized to average value of maxima at equator for all cases)
• Only a burst between -75° and -90° would fit the extinction data.