

# Terrestrial Effects of Ionizing Radiation Events

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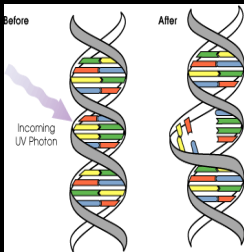
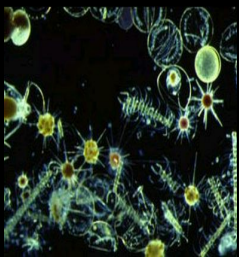
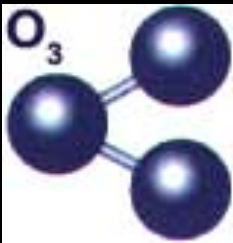
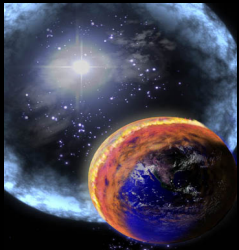
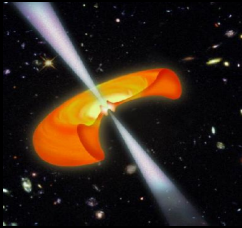
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# Effects of Ionizing Radiation

- Direct effects are limited:
  - Redistributed photon energy ( $\gamma \rightarrow$  UV)
    - High energy primaries  $\rightarrow$  GRBs (10 s, hemisphere)
  - High energy CRs: direct and/or secondaries
    - But, flux is small
- Atmospheric effects are more important:
  - Ionization creates  $\text{NO}_x$  compounds (NO,  $\text{NO}_2$ )
  - Catalytically destroy  $\text{O}_3 \rightarrow$  Enhanced Solar UV
  - Recovery takes years (up to a decade)

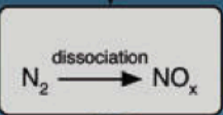


Approx. effective range
Approx. frequency

1 AU (1.5 x10 <sup>8</sup> km)	10 pc (3 x10 <sup>14</sup> km)	1 – 100 kpc (3 –300 x10 <sup>16</sup> km)	galaxy-wide
10 <sup>2</sup> – 10 <sup>3</sup> years	10 <sup>8</sup> – 10 <sup>9</sup> years	10 <sup>5</sup> – 10 <sup>9</sup> years	10 <sup>8</sup> – 10 <sup>9</sup> years



Extreme ionizing radiation event



atmospheric excitation and reemission [8.6]

catalytic [8.1]  
 destruction of ozone shield

NO<sub>2</sub> shading of visible insolation [8.4]

Post-perturbation oxidation of NO<sub>x</sub> [8.5]

direct radiobiological hazard [8]

enhanced solar UV penetration

global cooling

nitric acid rain-out

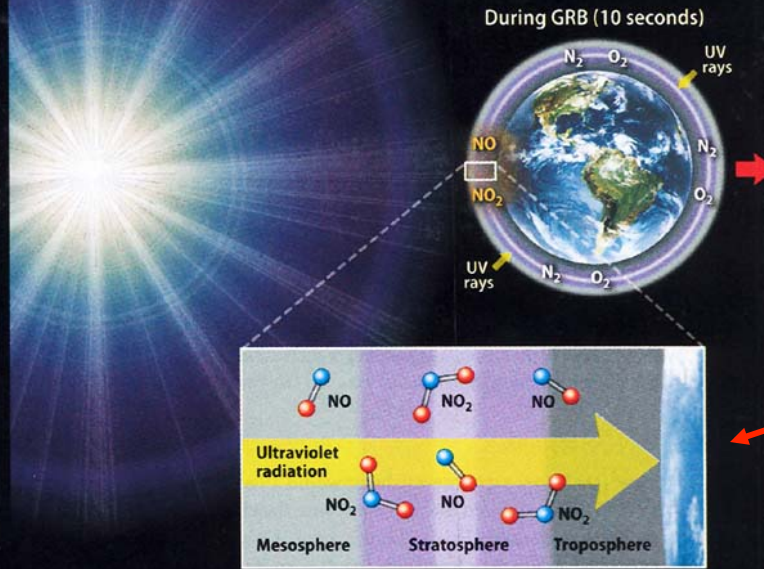
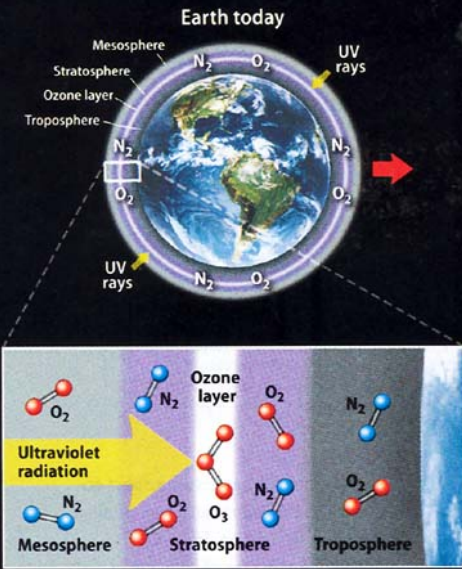
nitrate fertilization

UV flash

Approx. effect duration
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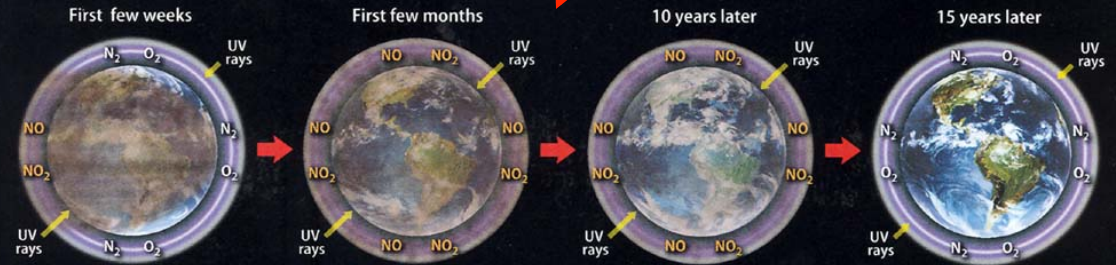
instantaneous      years – decades      NO<sub>2</sub> shading lasts years, but climatic effect could persist Myr      years      years      instantaneous

# How a gamma-ray burst would affect Earth



**AFTER:**  
Solar UV reaches surface,  
 $NO_2$  haze darkens

**BEFORE:** UV blocked by  $O_3$



After the first few weeks,  $NO$  and  $NO_2$  slowly destroy the ozone layer. These compounds spread by diffusion and wind, first around the equator and eventually as far as the North and South poles. As the ozone is destroyed, more UV-B radiation hits Earth's surface — an increase of roughly 50 percent, which is enough to damage DNA.

After a few months, the entire planet is covered in toxic brown gas. While the ozone has partially returned (20-percent below normal), UV-B radiation still poses a severe threat to life on Earth.

Over time, the atmosphere transports  $NO$  and  $NO_2$  to lower altitudes. The toxic gases react with water to form nitric acid, and precipitate out of the atmosphere as acid rain and snow.

The atmosphere is back to normal, but the damage is done. Fifteen years of increased UV-B radiation and toxic smog has not only killed off much land life and near-surface marine life, but it may have also tipped the climate balance, sending Earth into global cooling.

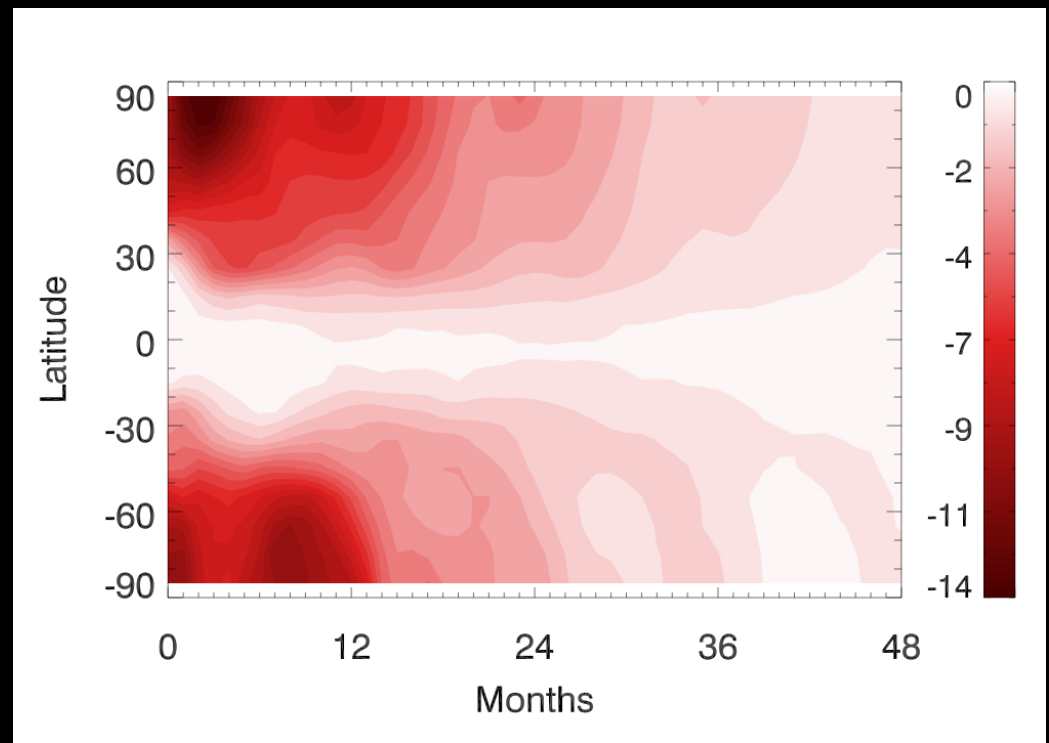
Astronomy Magazine,  
Oct. 2005

# Modeling Atmo Effects

- Compute atmospheric ionization from primaries (photons and/or CRs)
- Ionization is a source of  $\text{NO}_x$ 
  - NASA GSFC 2D atmo chemistry & dynamics model
- Run the model with pre-industrial conditions.
- Analyze changes in  $\text{O}_3$ 
  - Compute enhanced surface UV, bio impact

# Atmo Effects: 1859 Solar Proton Event

- O<sub>3</sub> depletion:
  - Max 5% global avg.
  - Similar to current
  - Recovery ~ 4 yrs



Thomas et al. 2007, GRL, 34, L06810

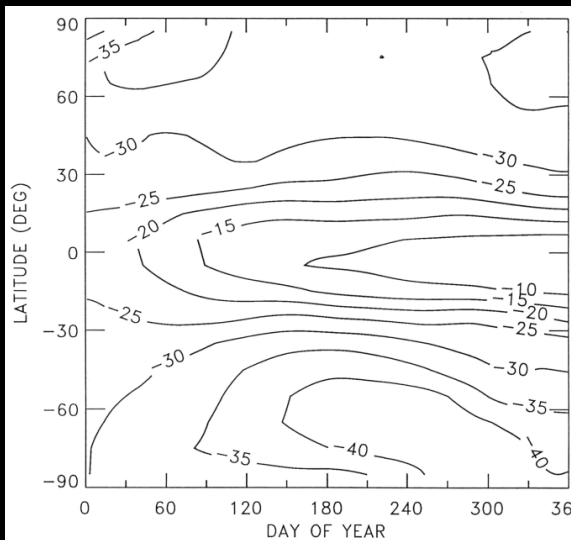
# Atmo Effects: SN 1987A scaled

- Most complete modeling from Gehrels et al. 2003 (ApJ):
  - Photon spectrum input; CRs just turned up GCR
  - Based on 1987A observations

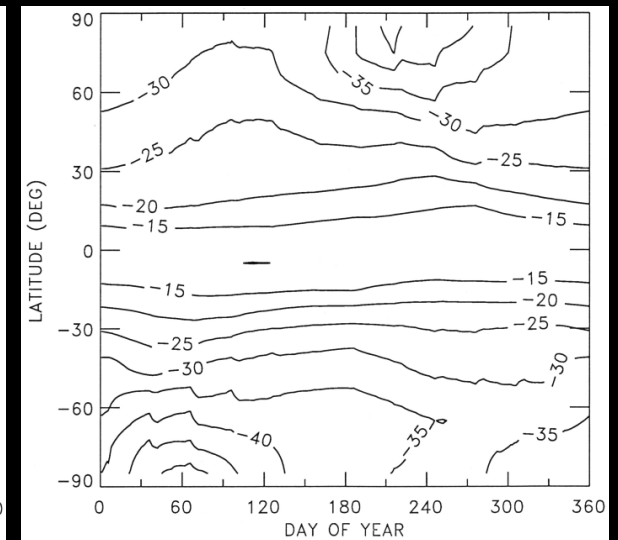
Depletion is similar for each component separately.

Up to 50-60% locally, 25% globally averaged

Photons @ 10 pc

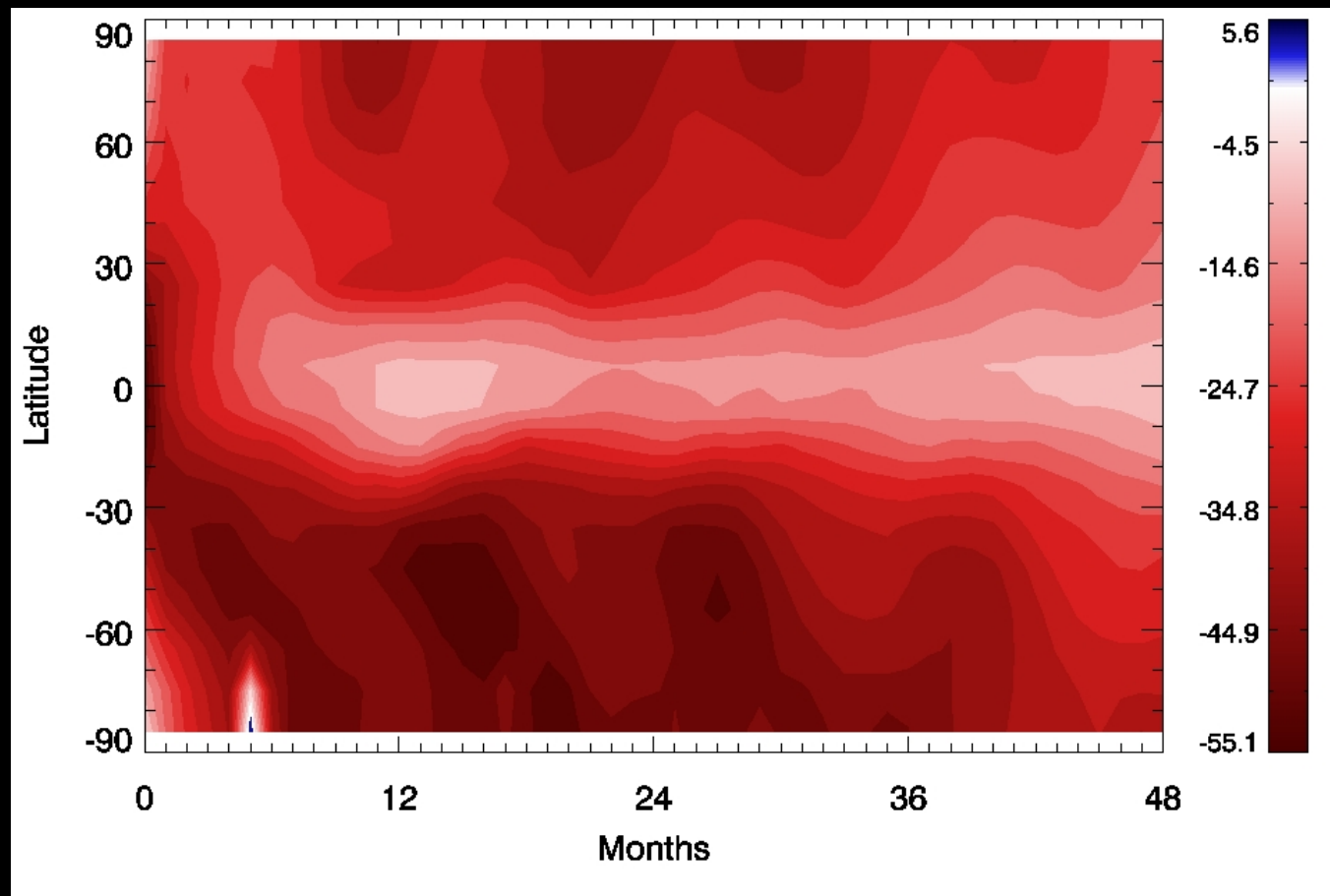


CRs @ 10 pc



# Atmo Effects: Long GRB

- O<sub>3</sub> depletion for burst over Equator, in March, at 2 kpc

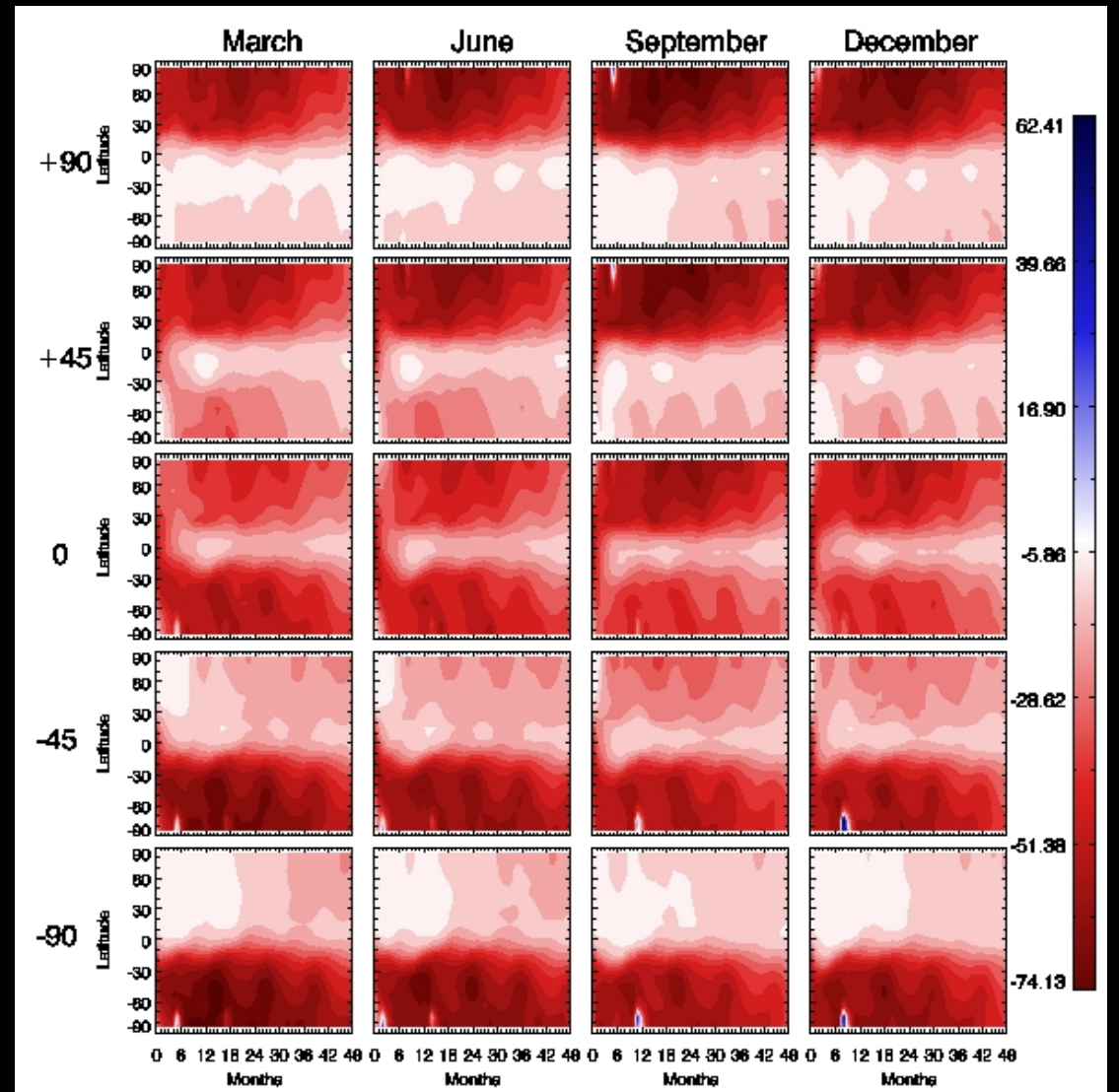


Thomas et al. 2005, ApJ, 634, 509



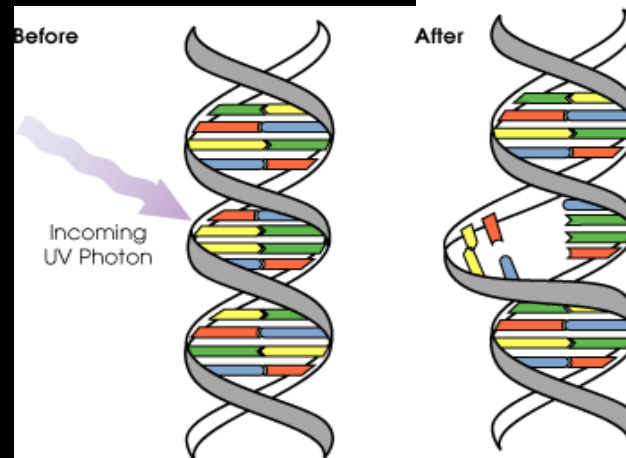
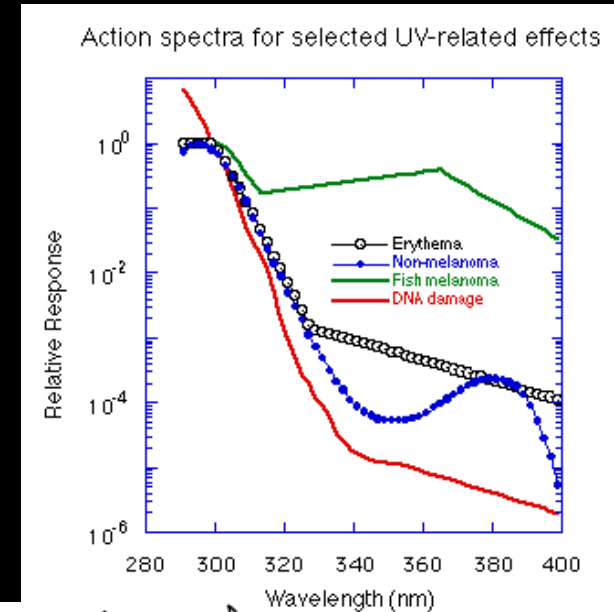
# Atmo Effects: Long GRB

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



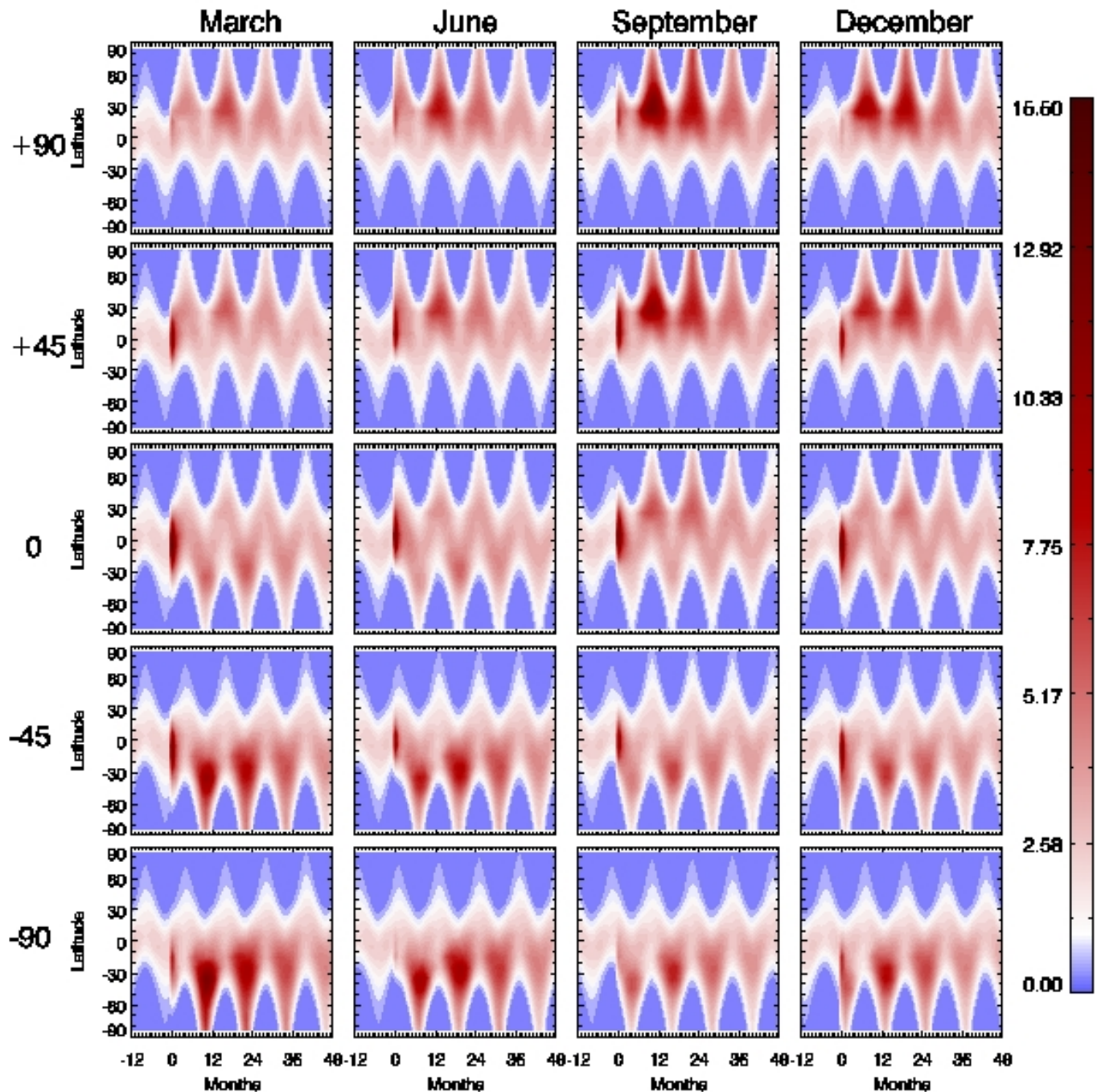
# Solar UV and Biological Effects

- Surface UVB (280-315 nm)
  - Solar UVB attenuated by O<sub>3</sub> 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.



# Steps toward Improvement

- To get more realistic damage estimates:
  1. Use a full radiative transfer model to get *spectral irradiance* at surface
    - And, use a *variety* of weighting functions
  2. Compute transfer of light into water
  3. Use weighting functions for the impact on phytoplankton primary productivity, integrated over the water column population.
    - In particular, newly measured BWFs for picophytoplankton species *Synechococcus* and *Prochlorococcus*

# Atmo Radiative Transfer Modeling

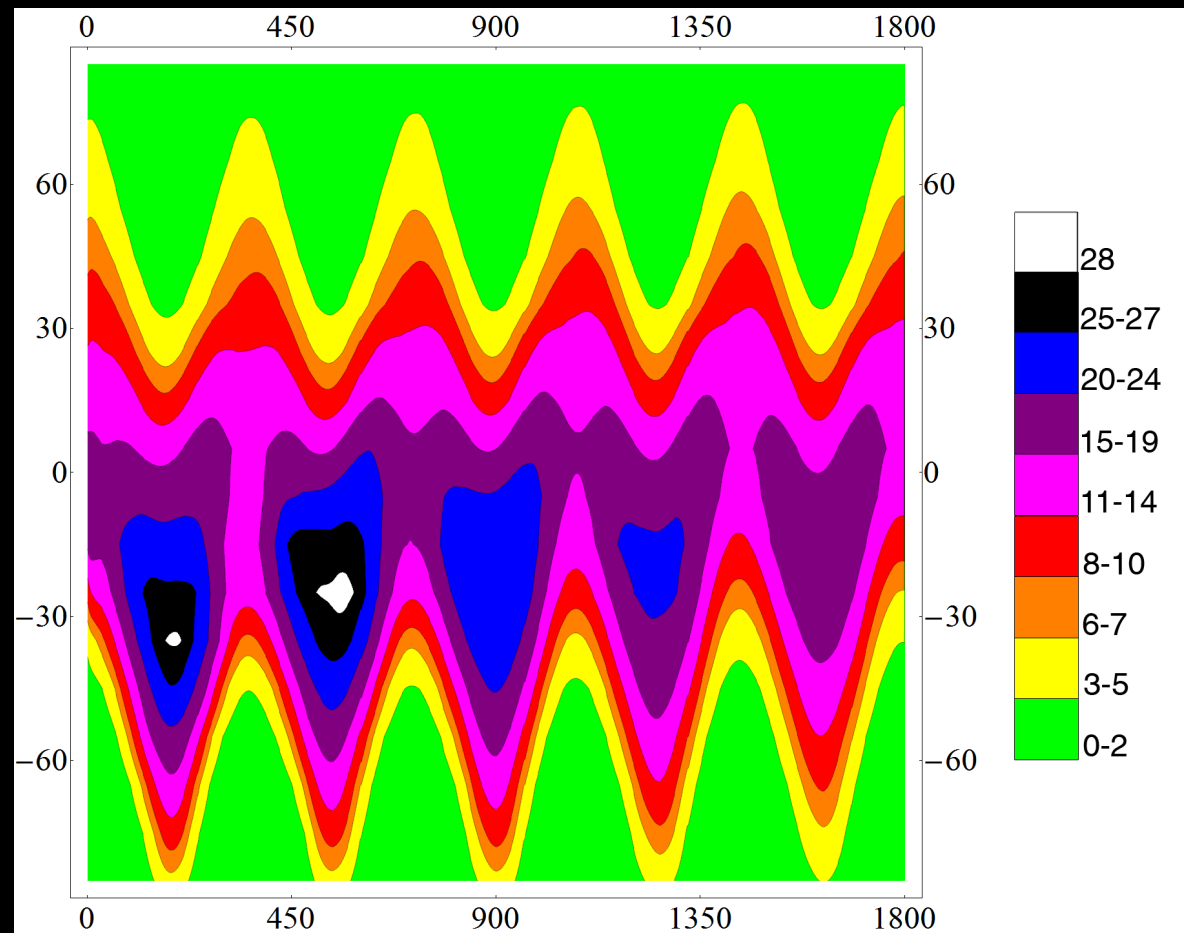
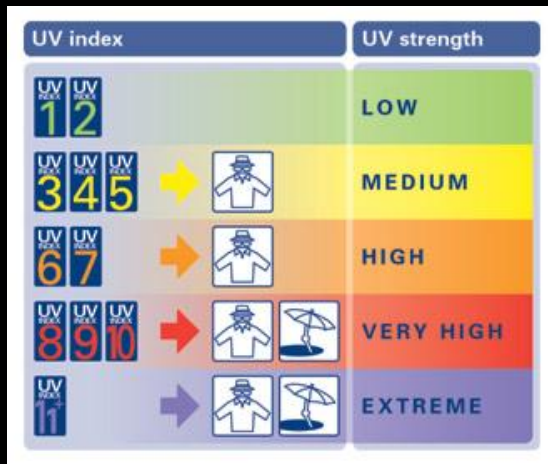
- TUV is a freely available atmo-RT model
  - Modified to read in O<sub>3</sub> and NO<sub>2</sub> profiles from atmo chemistry/dynamics modeling
- Output surface values:
  - Spectral irradiance from 280-700 nm
  - Total irradiance in UVB, UVA
  - Relative effects measured by various built-in weighting functions

# Some Results

## GRB over S.Pole, in June

(candidate for the end-Ordovician extinction)

- UV Index



# More Results

## GRB over S.Pole, in June

- At 25 deg South, 560 days (1.6 years) after burst (Jan. 16)

Quantity	% Change (GRB vs. Normal)
O <sub>3</sub> column density	-52
NO <sub>2</sub> column density	+2517
UV index (WMO, 1994)	+128
UVB irradiance	+66
UVA irradiance	-2
Erythema, humans (Anders et al., 1995)	+137
Phytoplankton (Boucher et al., 1994)	+83
Phytoplankton, <i>Phaeodactylum</i> sp. (Cullen et al., 1992)	+26
Phytoplankton, <i>Prorocentrum micans</i> (Cullen et al., 1992)	+40
Cataract, pig (Oriowo et al., 2001)	+100
Plant damage (Flint & Caldwell, 2003)	+49
DNA damage, in vitro (Setlow, 1974)	+310

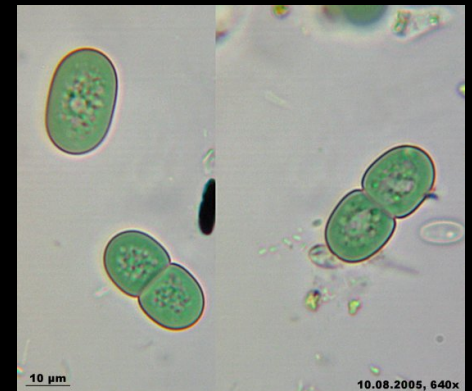
# Primary Productivity

- Computing the impact on primary productivity in the water column gives us an *integrated value*
- Removes most of the bio issues we had:
  1. Organisms aren't bare DNA
  2. Marine organisms live in and under the water, not just on surface (UV attenuated)
  3. Primary producers have repair mechanisms, and can move up and down in the water column

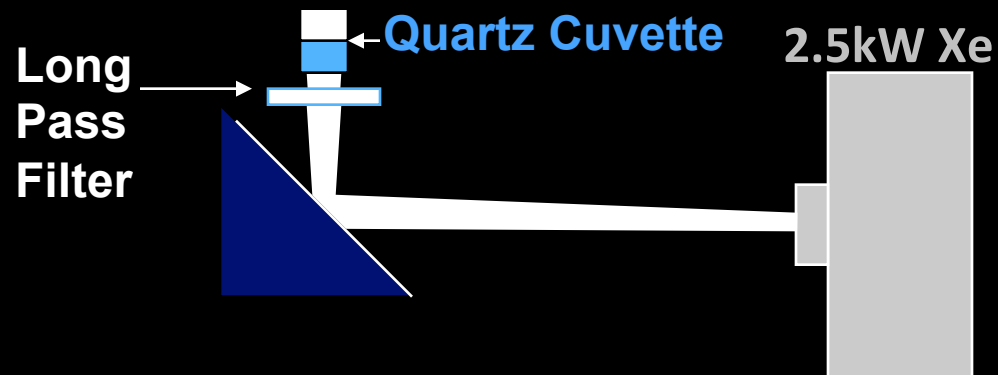
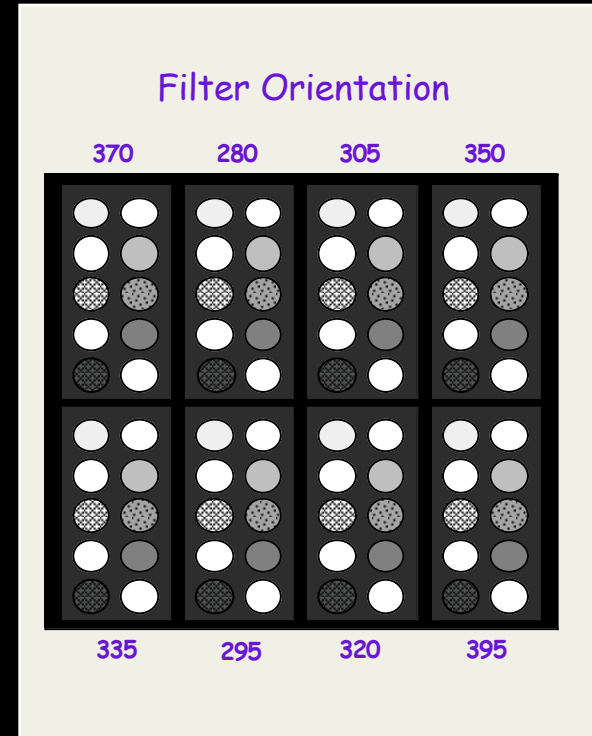


# Why Phytoplankton?

- Live in oceans, lakes, etc.
- Form the **base of the food chain** in these bodies of water
  - *Synechococcus* and *Prochlorococcus* are prevalent in mid-latitudes
- Produce half the world's O<sub>2</sub> supply
  - And consume CO<sub>2</sub> in the process
- Potentially vulnerable to increases in UV

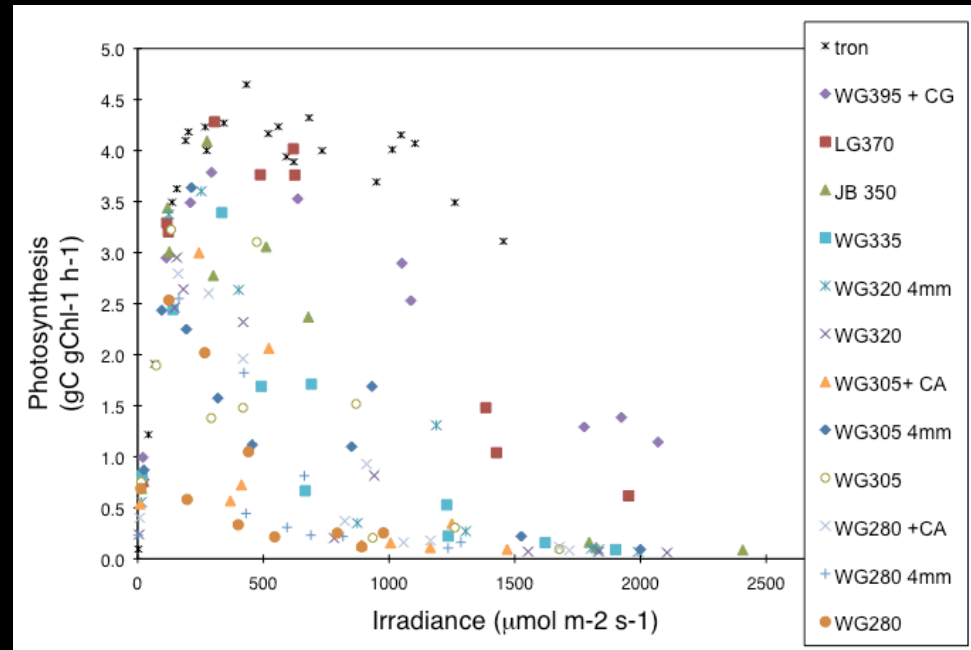
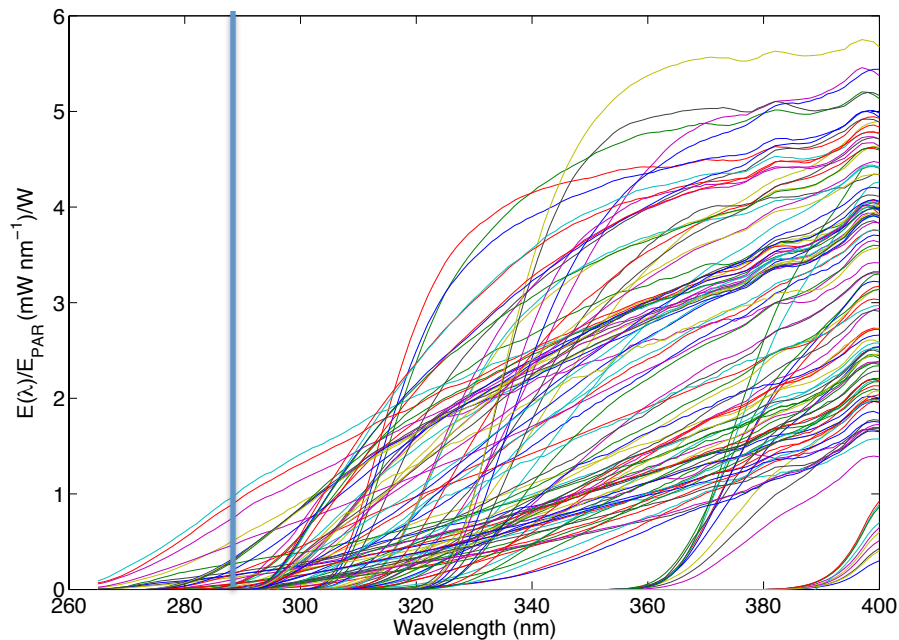


# The Photoinhibitor



A Polychromatic Incubator for Experimental UV Exposures

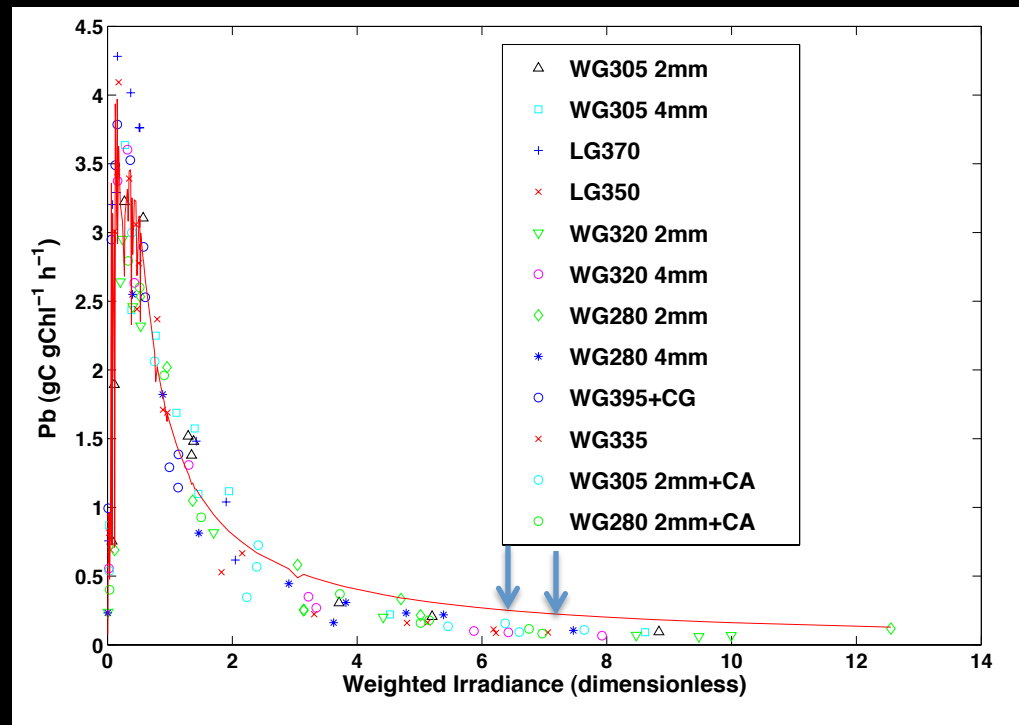
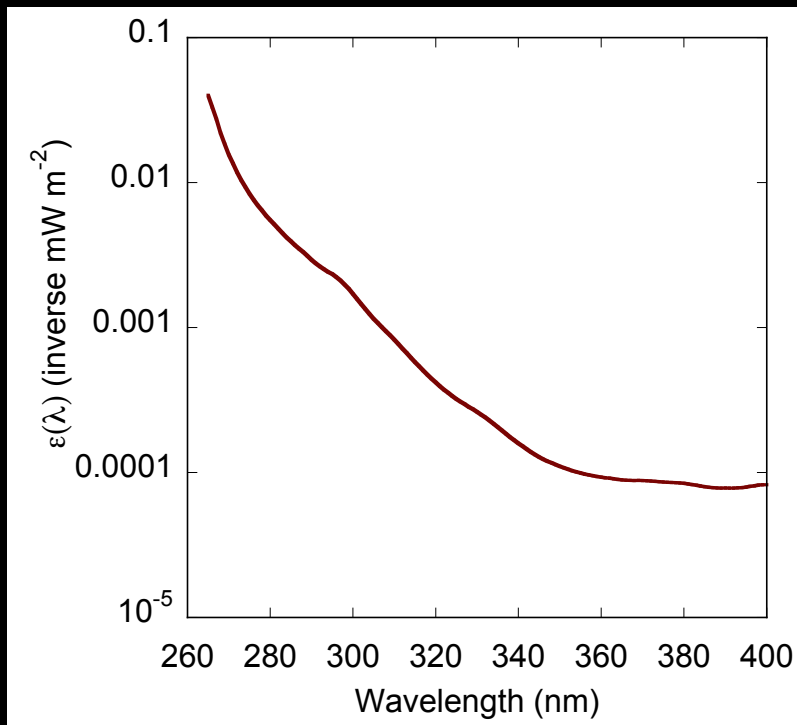
# Photoinhibition Exposure - Response



120 Spectral Treatments – some exposures extend below 290 nm

12 Cutoff filters x 10 Exposure Levels

# BWF – Photosynthesis Model



Preliminary Observations from Model Results:

-Ambient Conditions have Strong Effects – Surface UV inhibits Photosynthesis by ~80%

-Modest Effect of Additional UV from GRB

Further Decrease in Photosynthesis Generally < 10% at Surface

# Resources and Acknowledgements

- Short review article on terrestrial effects of GRBs
  - “Gamma-Ray Bursts as a Threat to Life on Earth” Thomas, *Int. J. Astrobiology*, vol. 8, 2009
- Recent review article on various kinds of events
  - “Astrophysical Ionizing Radiation and Earth: A Brief Review and Census of Intermittent Intense Sources” Melott and Thomas, *Astrobiology*, vol. 11, 2011
- **These and other papers available at [arXiv.org](http://arXiv.org)**
  - Or, email me: [brian.thomas@washburn.edu](mailto:brian.thomas@washburn.edu)
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