Consequences of astrophysical ionizing radiation events for Terrestrial Planets

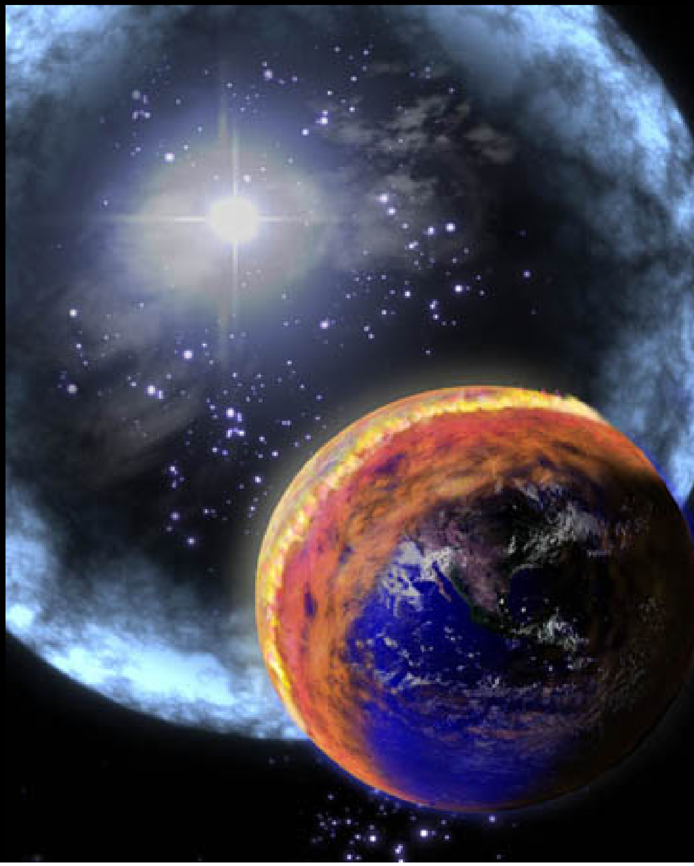
Adrian L. Melott

Dept. Physics & Astronomy, University of Kansas

Brian Thomas, Washburn University

Dimitra Atri, Tata Institute of Fundamental Research

Drew Overholt, University of Kansas



KU ASTROBIOPHYSICS
WORKING GROUP

Non-terrestrial planets?

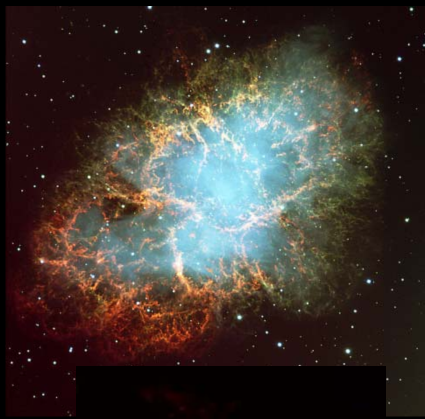
Best examples? Mars, Europa Surfaces exposed, radically different environment

Underground/Water under Ice? These *do* have terrestrial analogs. These environments are shielded from nearly all photons, cosmic rays (~ protons) but might be vulnerable to muons from high-energy comic rays (nearby supernovae, gamma-ray bursts).

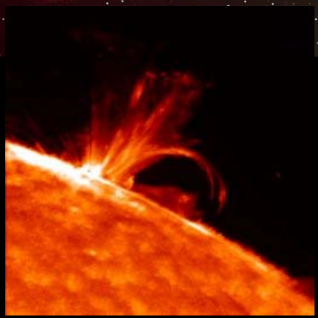
Paleo-Earth? O_2 and CO_2 levels not known; organic haze may have provided UV shielding…still, muons will be relevant.

Some ionizing sources and approximate interval for delivering 100 kJ/m^2 at Earth

“Long” Gamma ray bursts at 2 kpc---few/10^8 y if we (extrapolate from extragalactic rate-- # beamed at us)
Prototypical event
(R<D) ~ 1 (events/Gy) (D/2 kpc)^2 (valid for D>100 pc)



“Short” GRBs: about 100-1000 times more common in our galaxy; harder spectrum, less power—marginally more frequent at 200 pc.

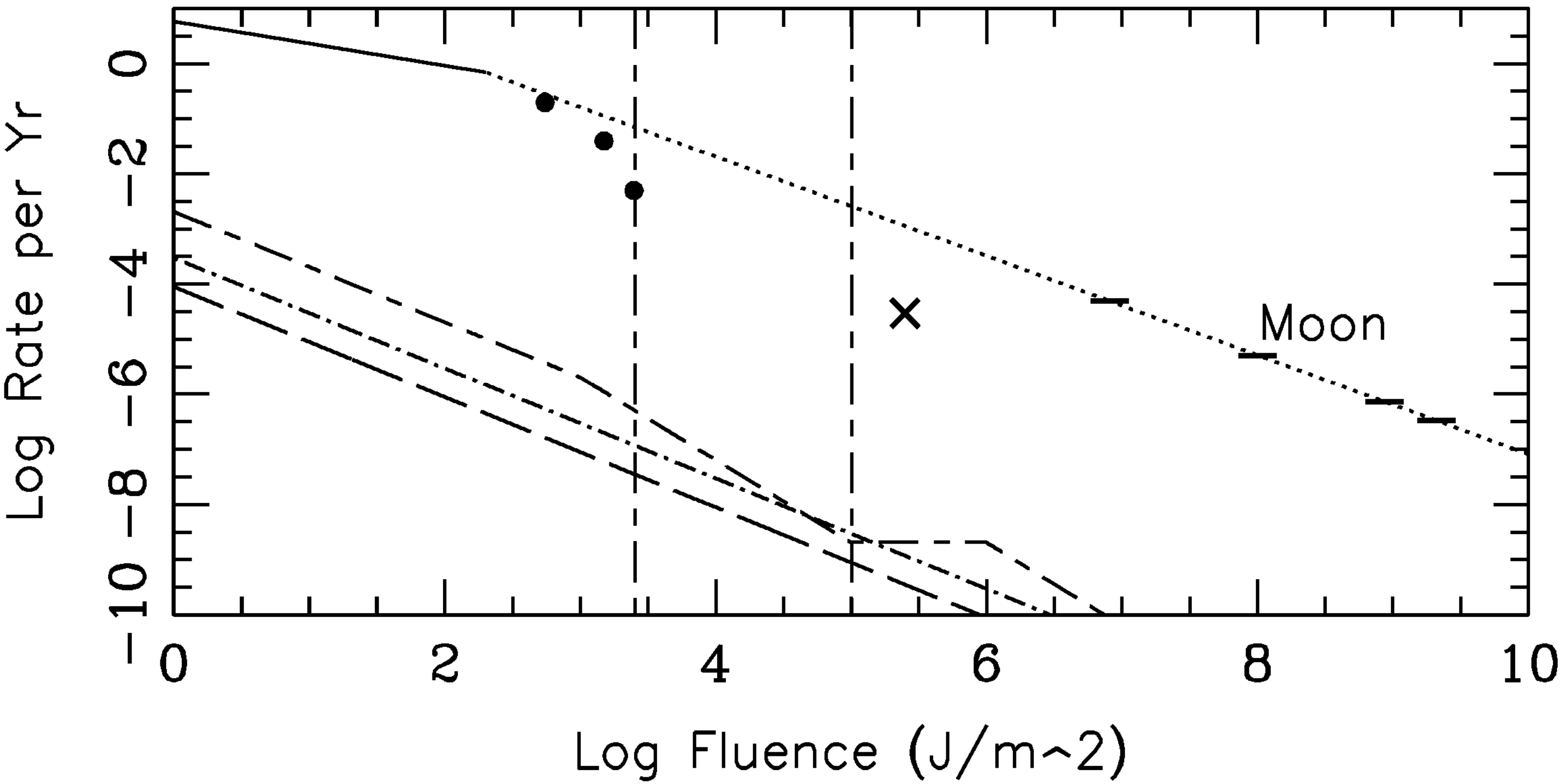


Supernovae at 10 pc---10^9 y (averaged galactic rate) *
R(<D) ~ 2 (events/My) (D/100 pc)^3 (valid for D<100 pc)

Solar flares---unknown—extrapolation of solar power-law distribution of flares suggests few 10^8 y—G star “superflares” have been observed (10^{31}J) but may not apply to the Sun *

Other potential hazards: soft gamma repeaters, post-burst GRB flares, unknown transients

Rates and fluences of the most dangerous ionization events



From "Astrophysical Ionizing Radiation and the Earth: A Brief Review and Census of Intermittent Intense Sources" (A.L. Melott and B.C. Thomas) *Astrobiology* **11**, 343-361 (2011) doi:10.1089/ast.2010.0603. Note: here photons, often gammas. Effects??

Ionizing photons and atmospheric chemistry

Opaque to gamma (100 m mean free path at STP for MeV photons, increasing with energy)

Energy deposition: 99+% into atmospheric chemistry --> N_2 , O_2

≤ 10^{-2} for most ionizing photons reaches ground as damaging UV/visible (Smith, Scalo & Wheeler Icarus 171, 229)

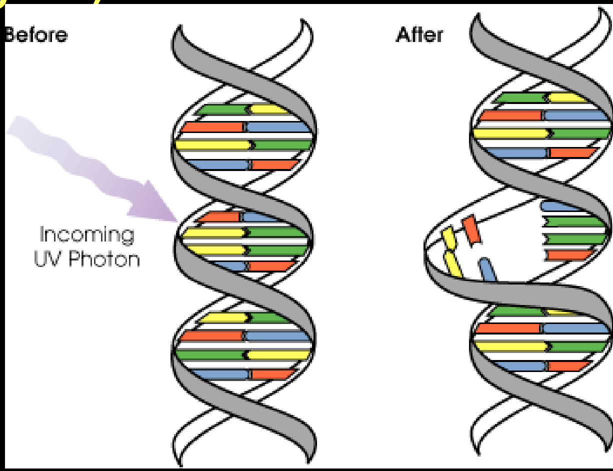
Effects of chemical changes to atmosphere:

1. Opacity - NO_2 (visible, brown—climate change?)
2. Nitric Acid Rain (fertilizer?)
3. Ozone depletion (UV shield destruction)

$NO + O_3 \to NO_2 + O_2$

$NO_2 + O \to NO + O_2$

Net: $O_3 + O \to O_2 + O_2$



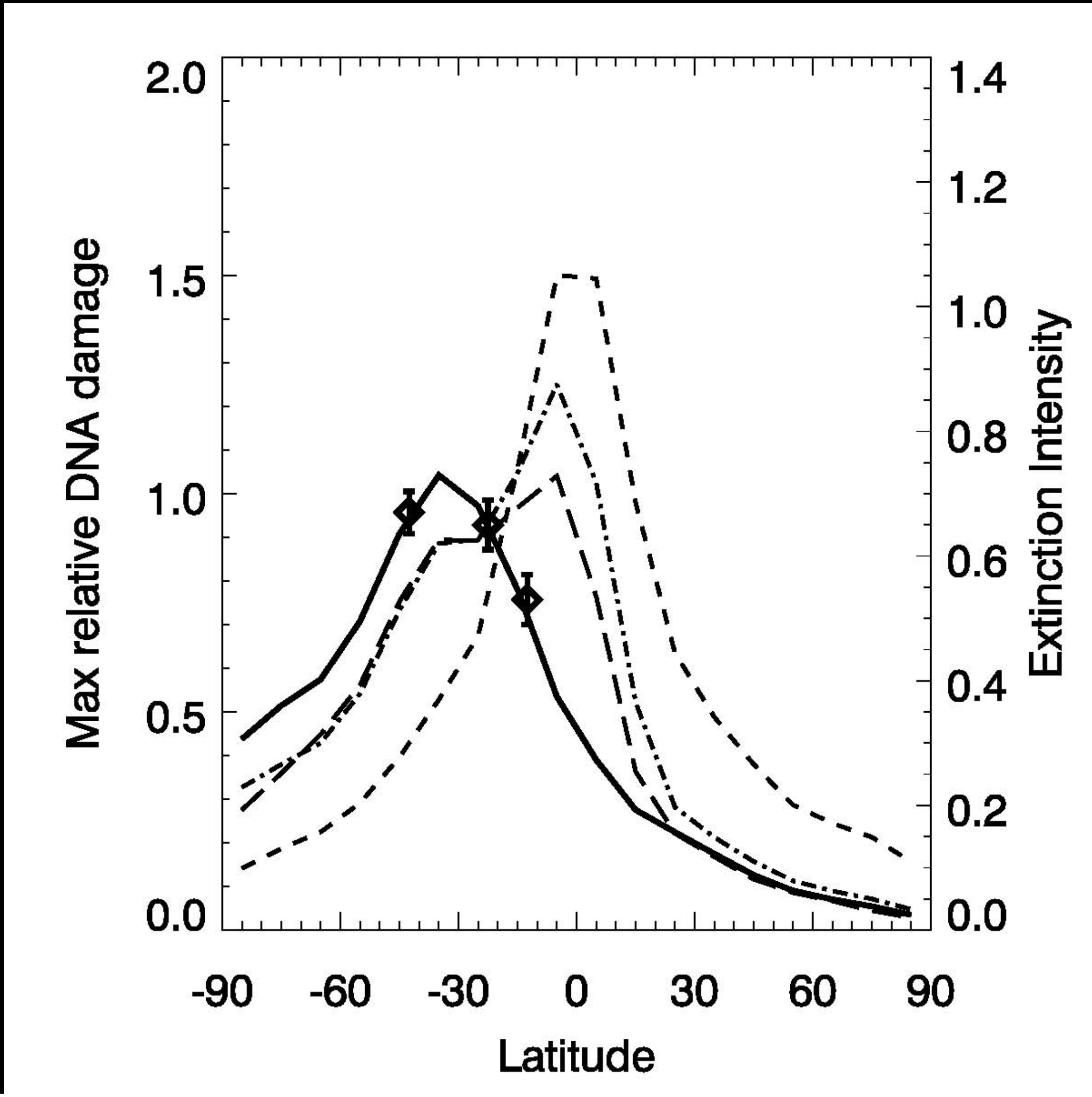
Primary result: greatly enhanced Solar UVB (290-320 nm) resulting potential for burns, DNA absorption/damage (cancer, mutations)

Systematics of end-Ordovician extinction

- Unexplained short period of glaciation
- Bias toward extinction of shallow water organisms, surface dwellers…
- Move to land accelerates after extinction event…and…

On the right we see plotted data from a group of simulations—the “red”—excess UV exposure—for a variety of southern hemisphere bursts. The data are extinction rates as a function of latitude. Can *anything* fit? Yes, a burst nearly over the (paleo) South Pole.

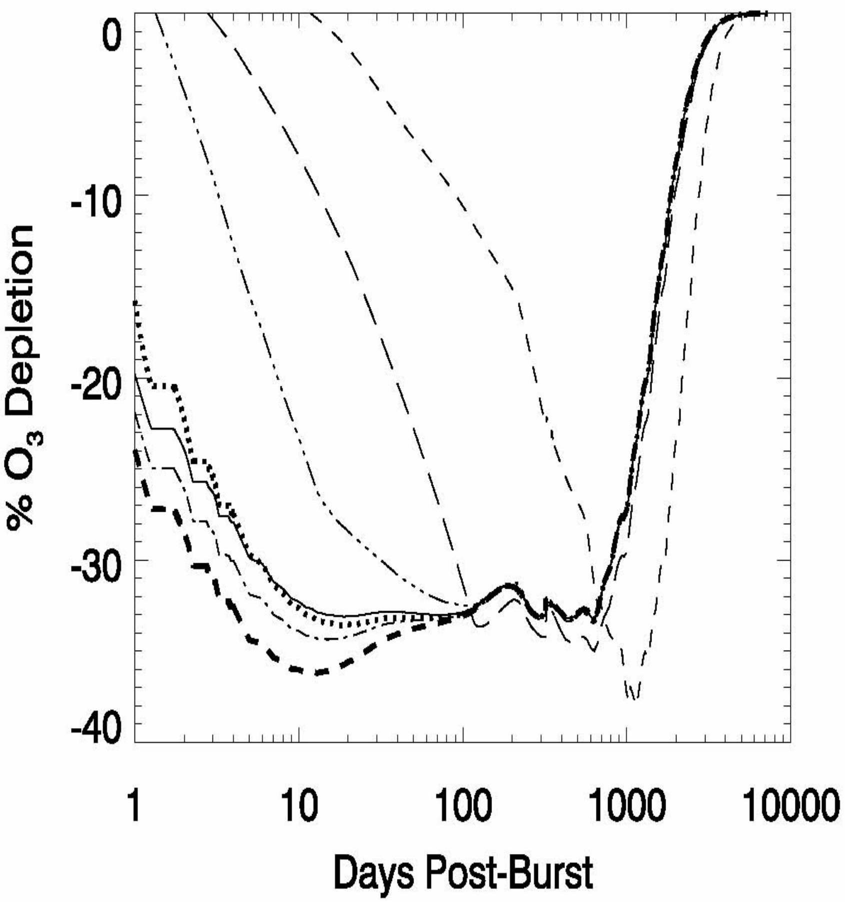
From Melott & Thomas, *Paleobiology* 35, 311 (2009).



How can we understand other events' impacts on the Earth?

- Short GRBs last as little as 100 ms
- Short GRBs have a harder spectrum
- Some GRBs have late-time flareups
- Solar flares last up to hours, have softer spectra than GRBs, and are often accompanied by protons
- The Xray afterglow of supernovae can last for months
- Supernovae may be superluminous, producing a strong emission in the optical
- Supernovae are expected to produce enhanced cosmic ray flux with long duration
- A galactic shock may provide periodic enhanced infusions of high-energy cosmic rays, lasting millions of years
- Is there a more general way to understand effects without doing detailed computations in each case? Photons first.

Variation in intensity with burst duration



The fractional global ozone depletion (relative to its unperturbed value) as a function of time for the fiducial case. The energy is deposited over 10^{-1} s (thick dash), 10s (dot-dash), 10^3 s (solid), 10^5 s (dotted), 10^6 s (dash-3dot), 10^7 s (long dash), and 10^8 s (short dash). Maximal global ozone depletion varies only slightly, though onset is delayed for long events. Slope discontinuities correspond to changes in photolysis reactions at sunset and sunrise in the stratosphere during the day (the burst is assumed to have taken place at noon). Oscillations over 100s of days are seasonal.

To first order, bursts of widely varying duration from 0.1 to 10^8 s ultimately result in very similar ozone depletion.

L. Ejzak et al., Astrophysical Journal, 654, 373 (2007).

Conclusions-varying photon irradiation parameters

- Irradiation predominantly directed at the northern or southern hemisphere tends to have results concentrated in that hemisphere.
- Bursts in the fall or winter have greater impact, as more ozone can ultimately be depleted.
- From earlier work, it is already known that for large fluences (~100 kJ/m^2) ozone depletion varies weakly with fluence.
- There is increasing depletion with increasingly hard source spectra, increasing from 2 keV but little increased effect above 20 Mev. This is caused by deeper penetration of ionizing photons into the stratosphere.
- Although ozone depletion by the end of the irradiation is greater for longer periods, the level of depletion reached (within a few months of the end of irradation) is ultimately the same for a given fluence and spectrum

Optical and near-optical photons??

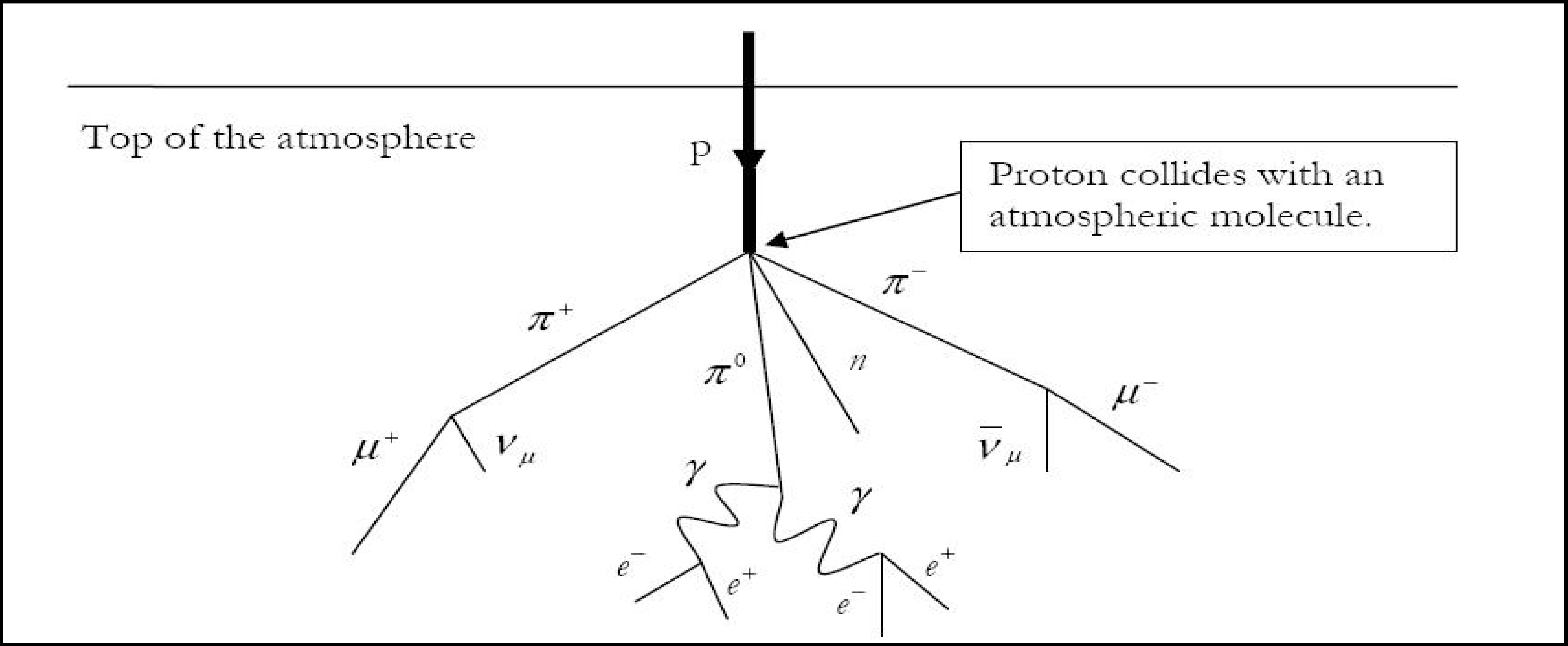
Downscattered and fluorescence photons from a GRB may produce a blinding UVA/UVB flash.

A typical Type II supernova remnant within 30 *pc* would produce about 0.1 W m^{-2}, initially blue light continuously at night for part of the biosphere. It appears that most mammals contain some poorly understood photoreceptor which is very sensitive around 300-500 *nm*, and can cause disruption of circadian rhythms, alter melatonin production, and even may be linked to increased cancer rates (Brainard, Reiter).

Cosmic Rays

- Nuclei accelerated to high energies, mostly protons
- A huge range of kinetic energies ranging over 15 orders of magnitude, up to the energy of a well-hit tennis ball!
- Sources include possible geomagnetic field reversals (loss of some shielding), Solar proton events, supernovae, unknown extragalactic sources, and a bow/termination shock on our Galaxy. “Probably not” GRBs (neutrino results).
- Propagation is complicated, because their paths are bent by magnetic fields at the Earth, Solar System, Galaxy: diffusive for low-energy CR.
- Low-energy Solar CR increase when the Sun is active, but its extended wind and magnetic field *suppress* galactic CR then.
- Supernovae probably produce large numbers of CR; perhaps most up to some energy level. For a nearby supernova, the photon blast would be followed by an extended period of enhanced CR.

Atmospheric propagation is complicated



1. Muons (μ) & neutrons are significant secondaries, but neutrons only at high altitude (think jetliners). Includes DNA, protein damage.
2. Nuclear reactions with air create ^{14}C, ^{10}Be and other isotopes widely used in tracing CR history. Also ionize air, may induce O_3 depletion.
3. CRs ionize the atmosphere, and may enhance low-level cloud cover; this *may* be a factor in promoting climate cooling due to increased albedo.

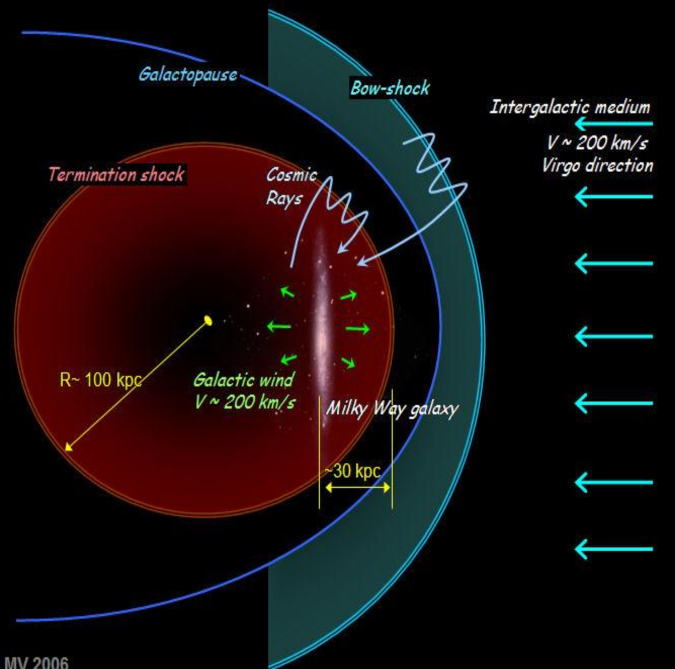
* Work published: Dimitra Atri, Drew Overholt

μ matter on the ground

- Most elementary particles don't reach the ground or else (such as neutrinos) they don't do much to the biota. Muons are the big exception.
- Normally, 0.4 mSv/yr on the surface comes from μ out of a total dose of 2.4 mSv/yr.
- μ can penetrate hundreds of meters of rock or 1 km of water.
- μ enhancements can be substantial in the extragalactic shock scenario, or a "nearby" supernova.

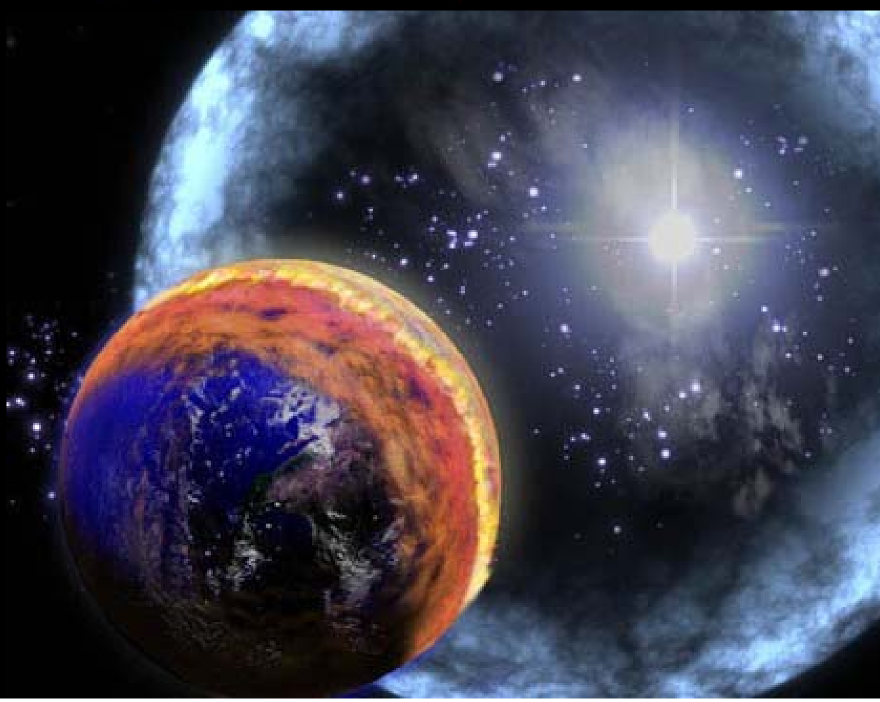
Important sources of CR enhancement

Hypothesis: every 62 Myr, as the solar system emerges on galactic north, there are excess cosmic rays due irradiation from a galactic bow shock.



Medvedev, MV 2006

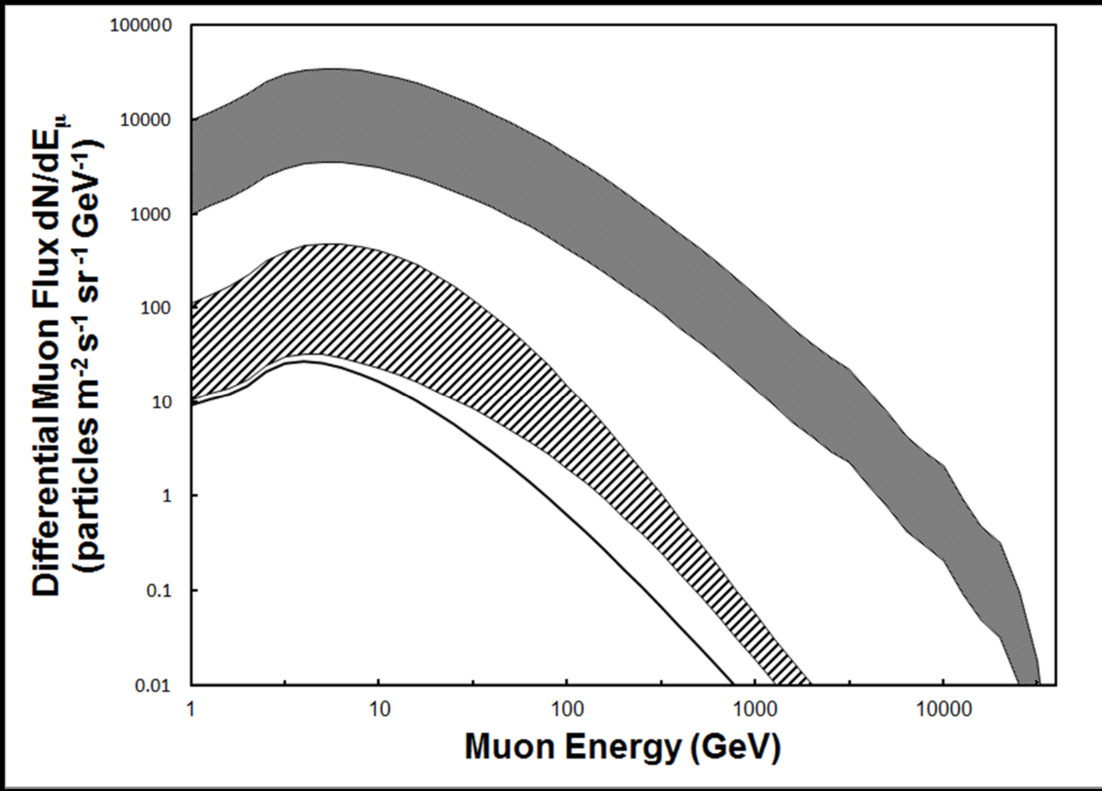
Prediction: every few hundred Myr, the Earth is irradiated by a supernova from within about 10 pc (31 ly) precipitating a mass extinction. ^{60}Fe in the oceans is residue of a "moderate" event a few Myr ago.



μ irradiation from CR enhancement

Solid line: present day μ flux on the ground.

Region filled by diagonal lines: every 62 Myr, the terrestrial radiation background goes up by a factor of 2-15 for perhaps 10 Myr. Cycle of biodiversity?



Dark shaded region represents irradiation from μ due to a nearby supernova—lasting hundreds of years. Radiation dosage increases by 100+ fold. Major extinction…Will penetrate about a km of water; works in non-oxygen atmosphere. However, a thick atmosphere or water/ice layer will protect. This should be a fairly generic threat.

Resources

Ionizing photons: "Astrophysical Ionizing Radiation and the Earth: A Brief Review and Census of Intermittent Intense Sources (Adrian L. Melott and Brian C. Thomas) *Astrobiology* **11**, 343-361 (2011)

Cosmic rays, biodiversity fluctuation: "Do extragalactic cosmic rays induce cycles in fossil diversity?" (Medvedev & Melott) *Astrophysical Journal* **664**, 879 (2007)

"Biological implications of high-energy cosmic ray induced muon flux in the extragalactic shock model" (D. Atri and A.L. Melott) *Geophysical Res. Lett.* **38**, L19203 (2011)

"Modeling high-energy cosmic ray induced terrestrial and atmospheric neutron flux: A lookup table" (A.C. Overholt, A.L. Melott, and D. Atri) *J. Geophys. Res*., submitted (2012).

Solar flares: "Modeling atmospheric effects of the September 1859 Solar flare" (Thomas et al.) *Geophysical Research Letters* **34**, L06810, 10.1029/2006GL029174 (2007).

http://kusmos.phsx.ku.edu/~melott/Astrobiology.htm

Research supported by NASA Astrobiology: Exobiology and Evolutionary Biology