Terrestrial Effects of High Energy Cosmic Rays

Cosmic Rays and the history of life on Earth

Collaborators: Adrian Melott (Kansas)
Brian Thomas (Washburn)

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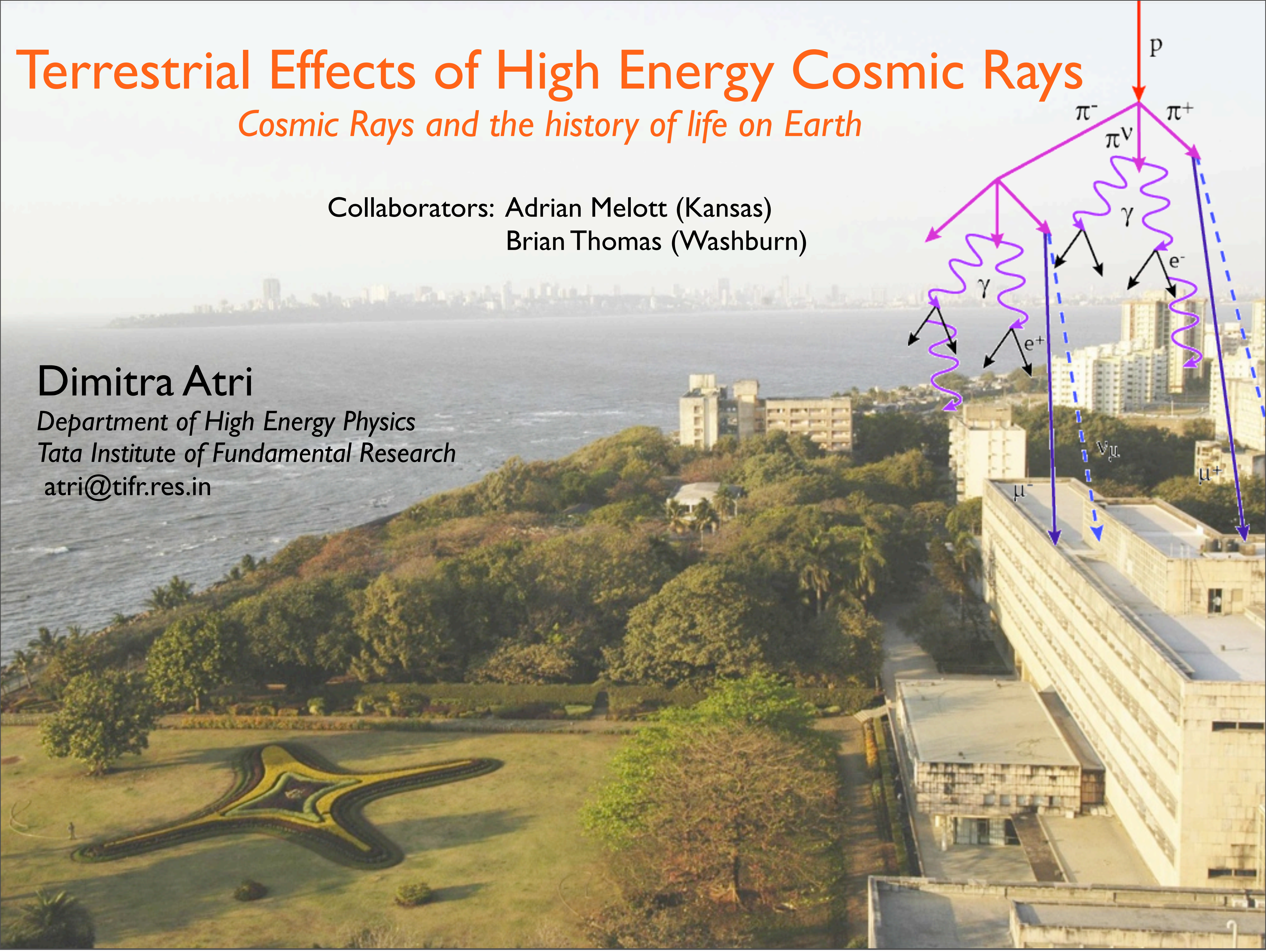

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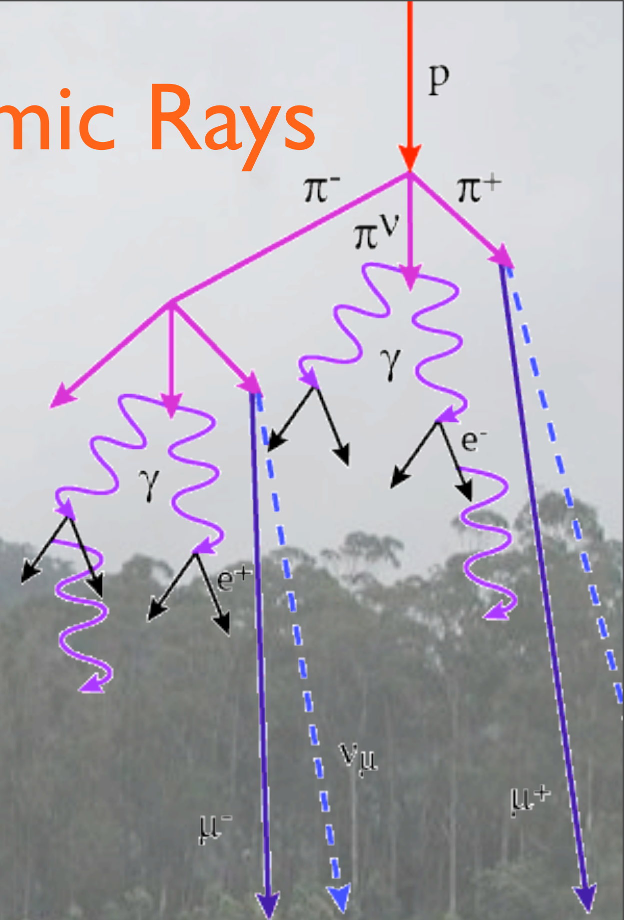

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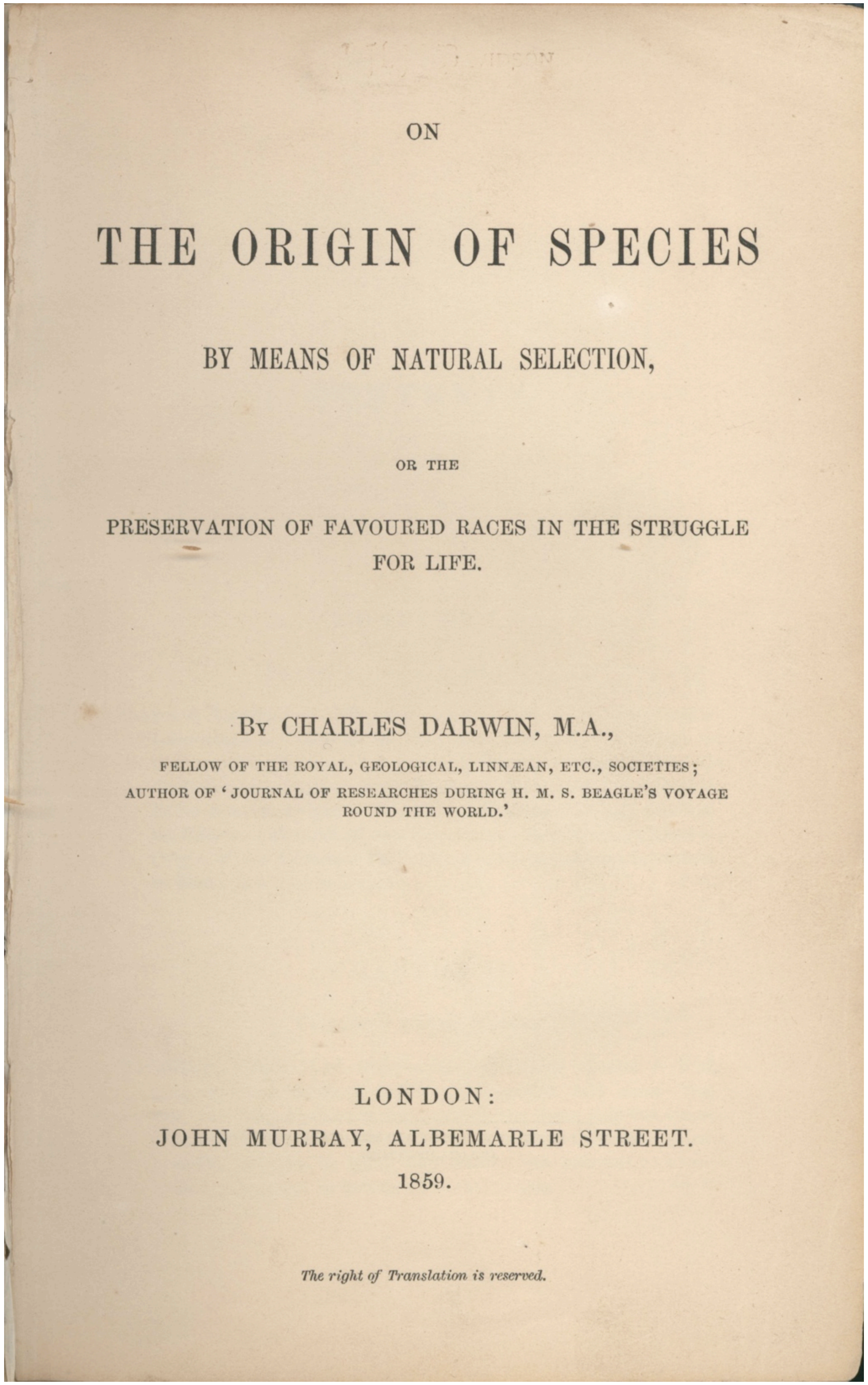

ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

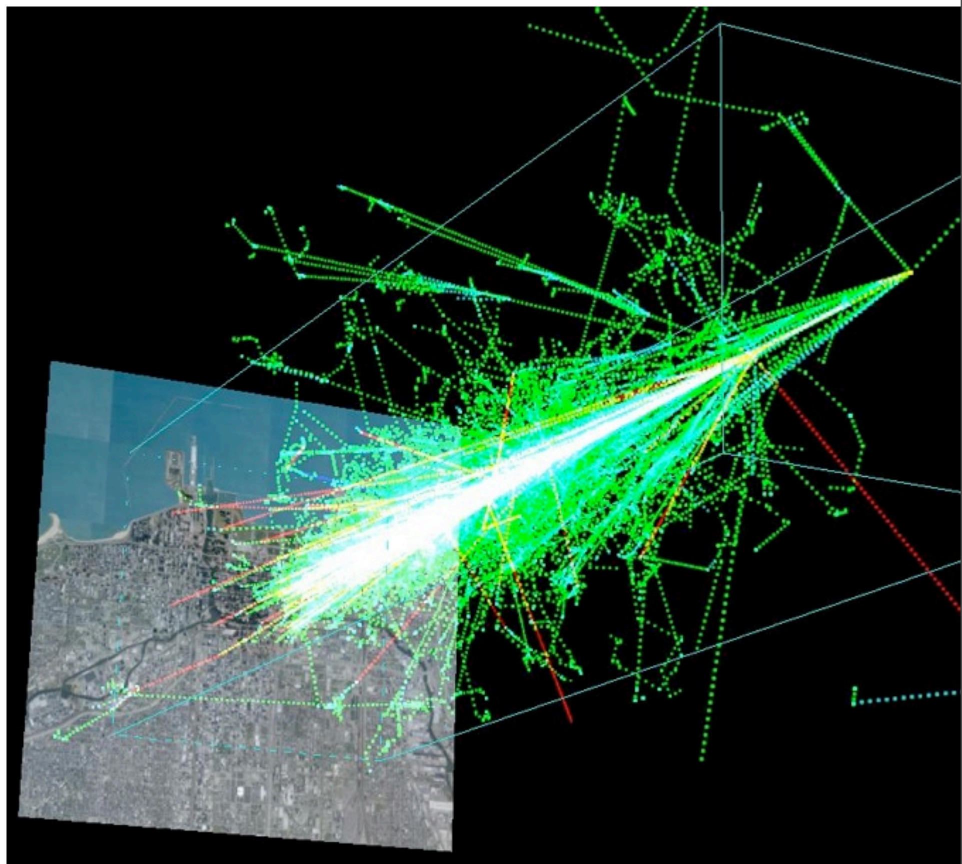
PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

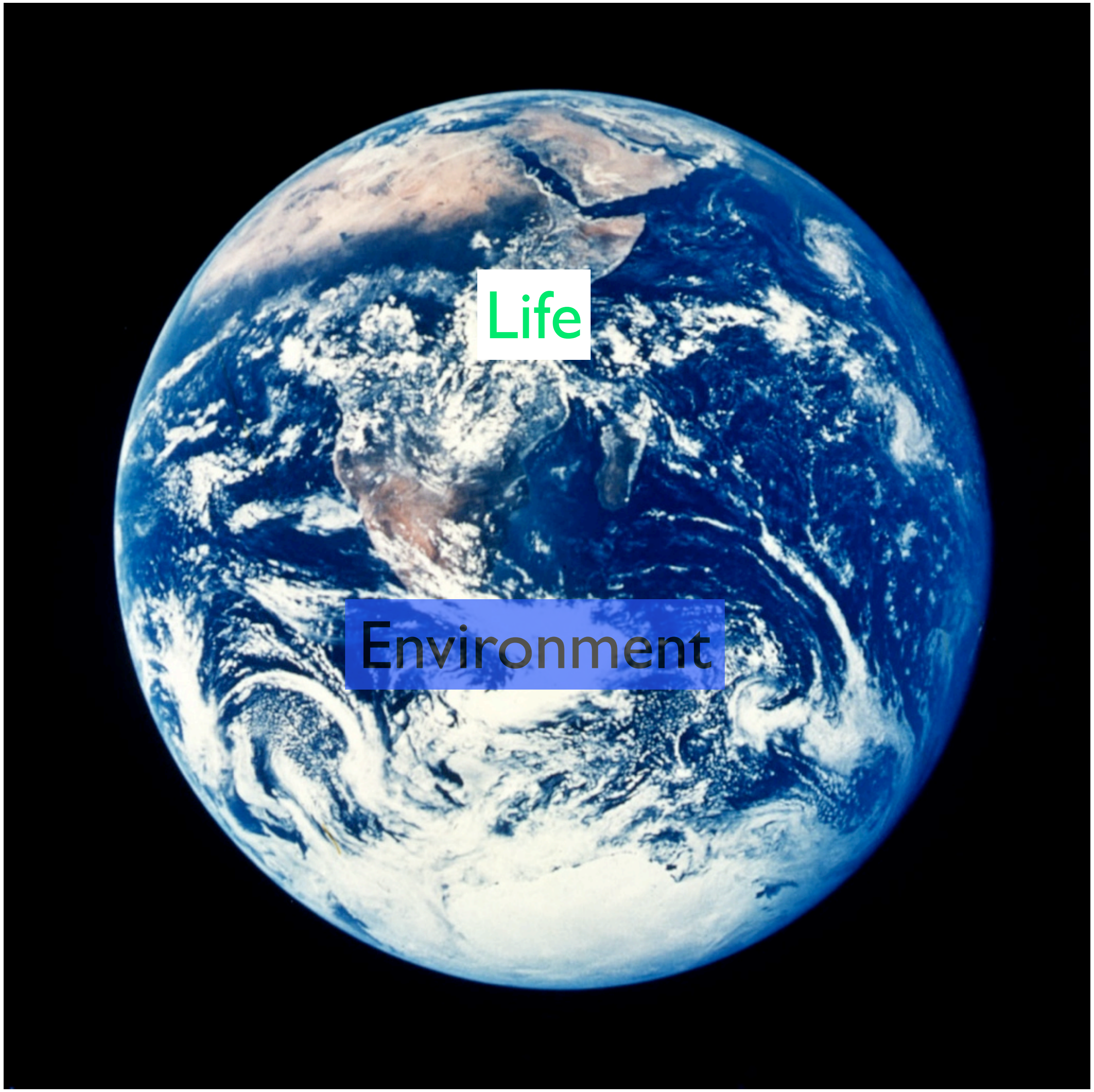
BY CHARLES DARWIN, M.A.,

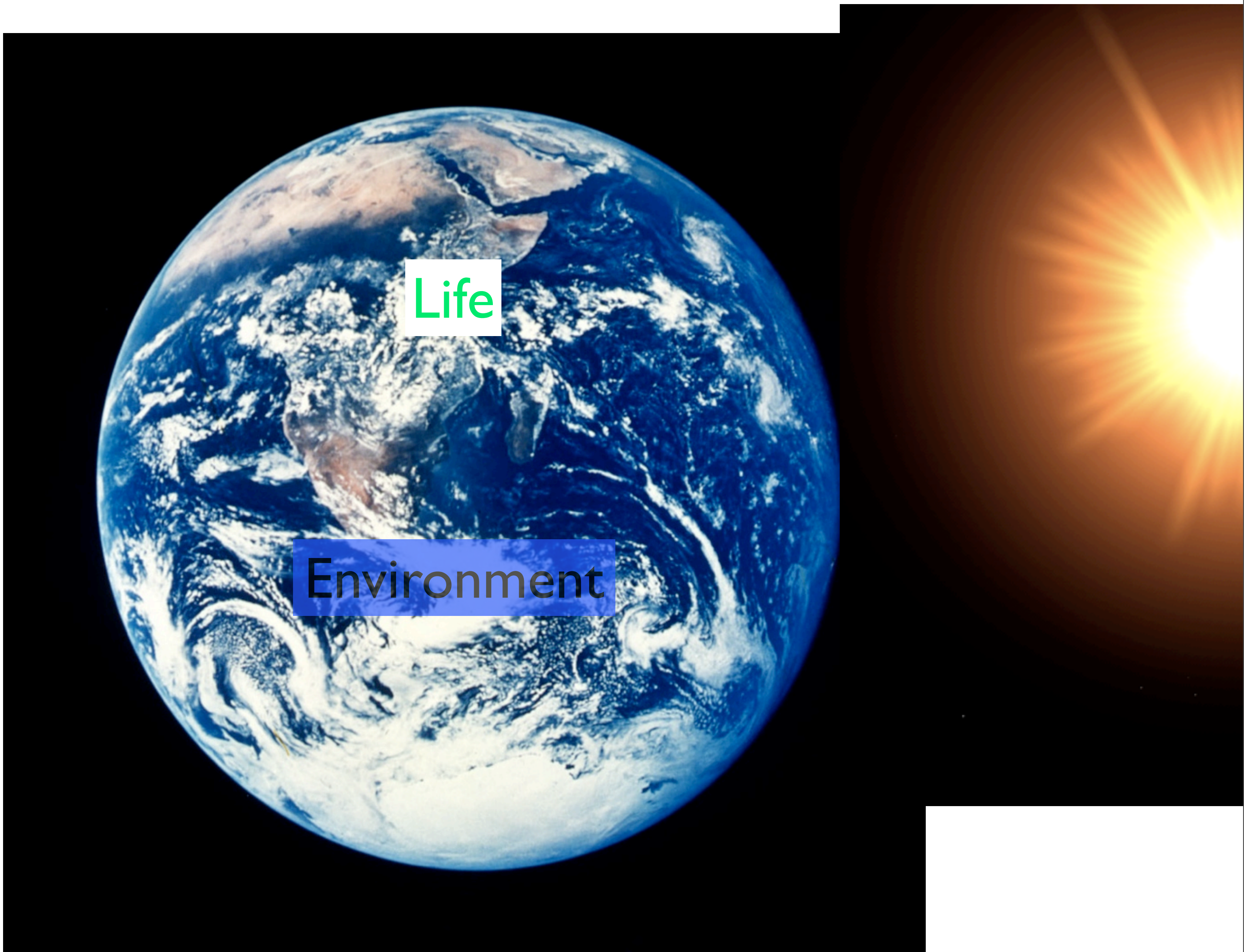
FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

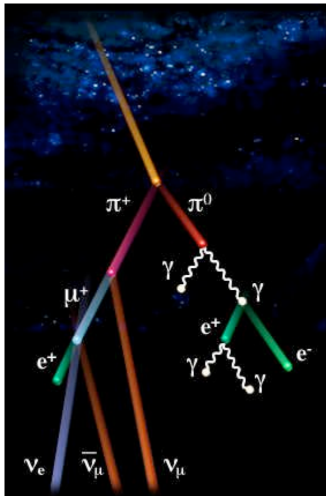
The right of Translation is reserved.

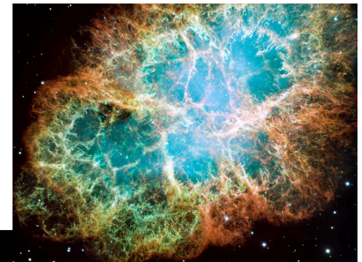


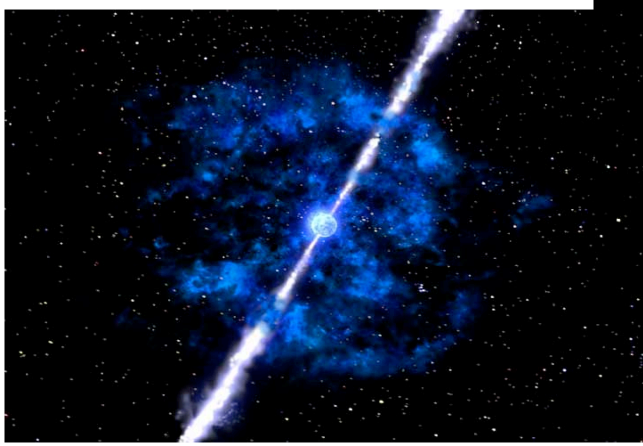

Life
Environment


Life
Environment

Environment







History of life on Earth

- Rohde and Muller, Cycles in Fossil Diversity, *Nature*, Volume 434, Issue 7030, pp. 208-210 (2005)
- It is well known that the diversity of life appears to fluctuate during the course of the Phanerozoic, the eon during which hard shells and skeletons left abundant fossils (0-542 million years ago). Here we show, using Sepkoski's compendium of the first and last stratigraphic appearances of 36,380 marine genera, a strong 62 +/- 3-million-year cycle, which is particularly evident in the shorter-lived genera. The five great extinctions enumerated by Raup and Sepkoski may be an aspect of this cycle.

- Gies and Helsel, Ice Age Epochs and the Sun's Path through the Galaxy, The Astrophysical Journal, Volume 626, Issue 2, pp. 844-848

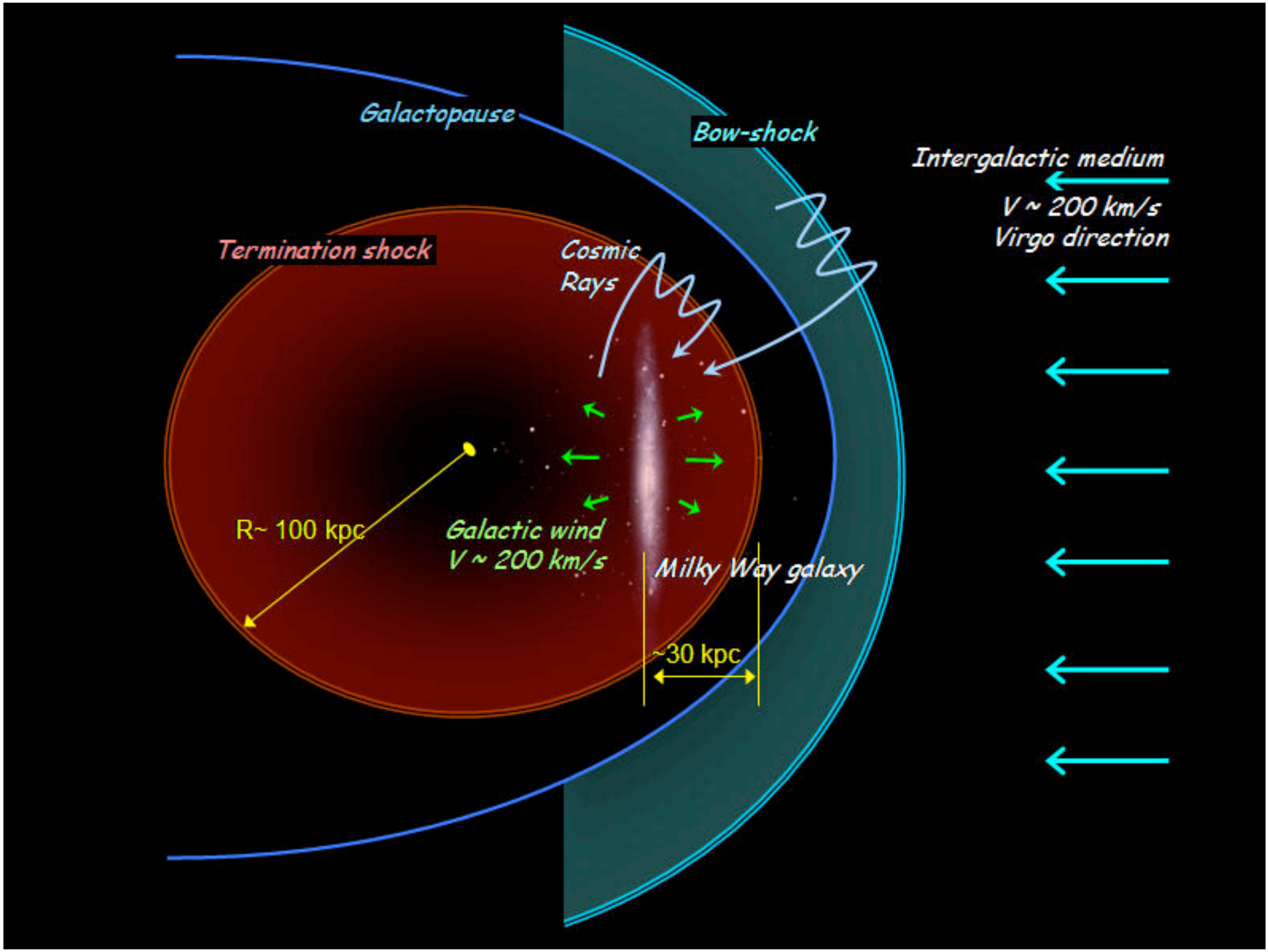
- We present a calculation of the Sun's motion through the Milky Way over the last 500 million yr. The integration is based on estimates of the Sun's current position and speed from measurements with Hipparcos and on a realistic model for the Galactic gravitational potential.

- SN ~ 10^{44} J, CR up to 10^{15} eV. ^{60}Fe evidence of a nearby SN. Incorrect CR treatment.

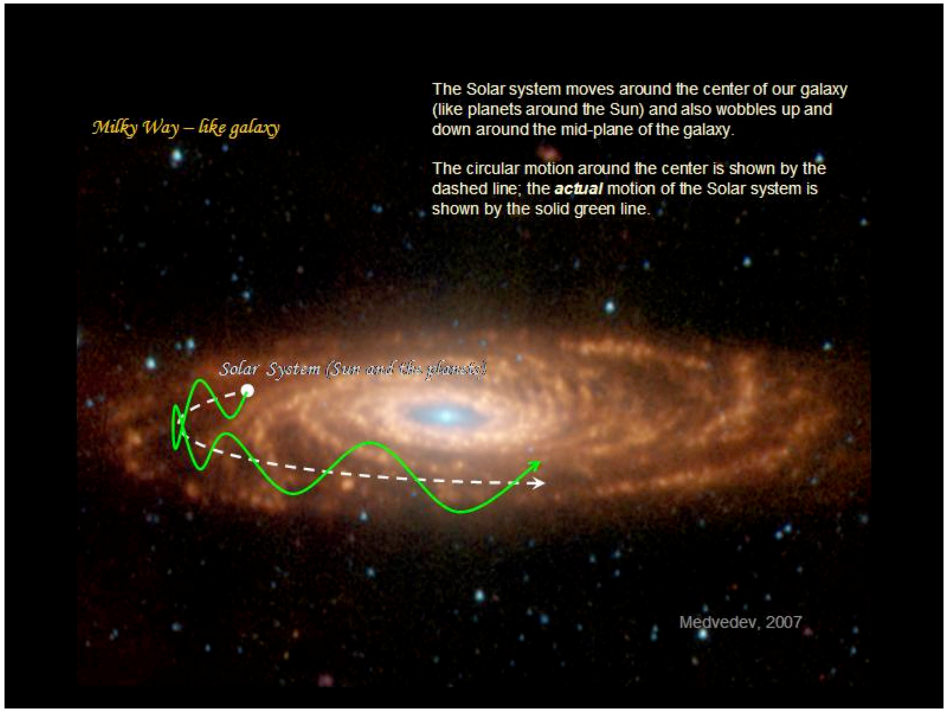
- GRB ~ 10^{47} J, CR up to 10^{18} eV (Dermer et al.). Once every ~ 1 Gy. A 3 kpc burst. Previous modeling with only photons.

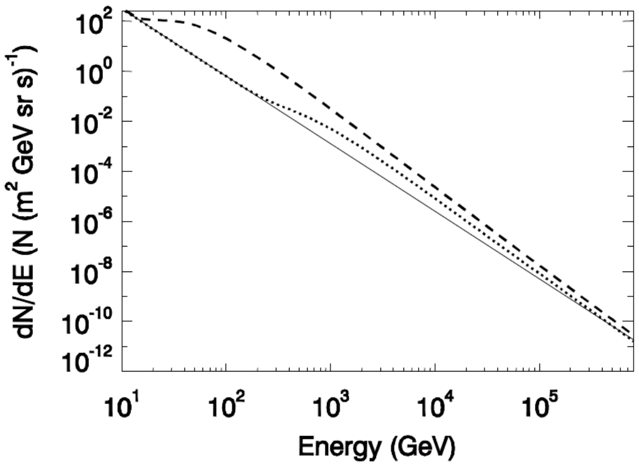
- Extragalactic Shock Model - Enhancement between 10 GeV - 1 PeV. Periodicity: ~ 62 Myr.

- Effects of intense Solar flares and Coronal Mass Ejections.


Galactopause
Bow-shock
Intergalactic medium
V ~ 200 km/s
Virgo direction
Termination shock
Cosmic
Rays
R~ 100 kpc
Galactic wind
V ~ 200 km/s
Milky Way galaxy
~30 kpc

Periodicity in terrestrial biodiversity





Enhanced spectra in the extragalactic shock model (Medvedev et al., 2007).

Melott and Bambach, 2010, "An ubiquitous ~62 Myr periodic fluctuation superimposed on general trends in fossil biodiversity: Part I, Documentation", Paleobiology.

Melott A., "Long-term cycles in the history of life: Periodic biodiversity in the Paleobiology database" PLoS ONE, 2008. 3(12).

Rohde, R. and R. Muller, "Cycles in fossil diversity". Nature, 2005. 434(7030): p. 208-210.

Medvedev M., Melott A., "Do extragalactic cosmic rays induce cycles in fossil diversity?" Astrophysical Journal (2007)

Two primary mechanisms of biological damage from Cosmic Rays

Indirect effect

Damage from *solar UVB by ozone depletion*. Cosmic rays ionize the atmosphere and deplete the ozone layer.

Direct effect

Damage by terrestrial *cosmic ray secondaries*, primarily muons.

Atmospheric Chemistry

NASA GSFC 2D photochemical code: - C. Jackman et al.

NOx compounds catalyze the conversion of O_3 to O_2. This leads to ozone depletion, which makes way to the harmful UVB (280-315 nm) radiation which is known to damage DNA and proteins.

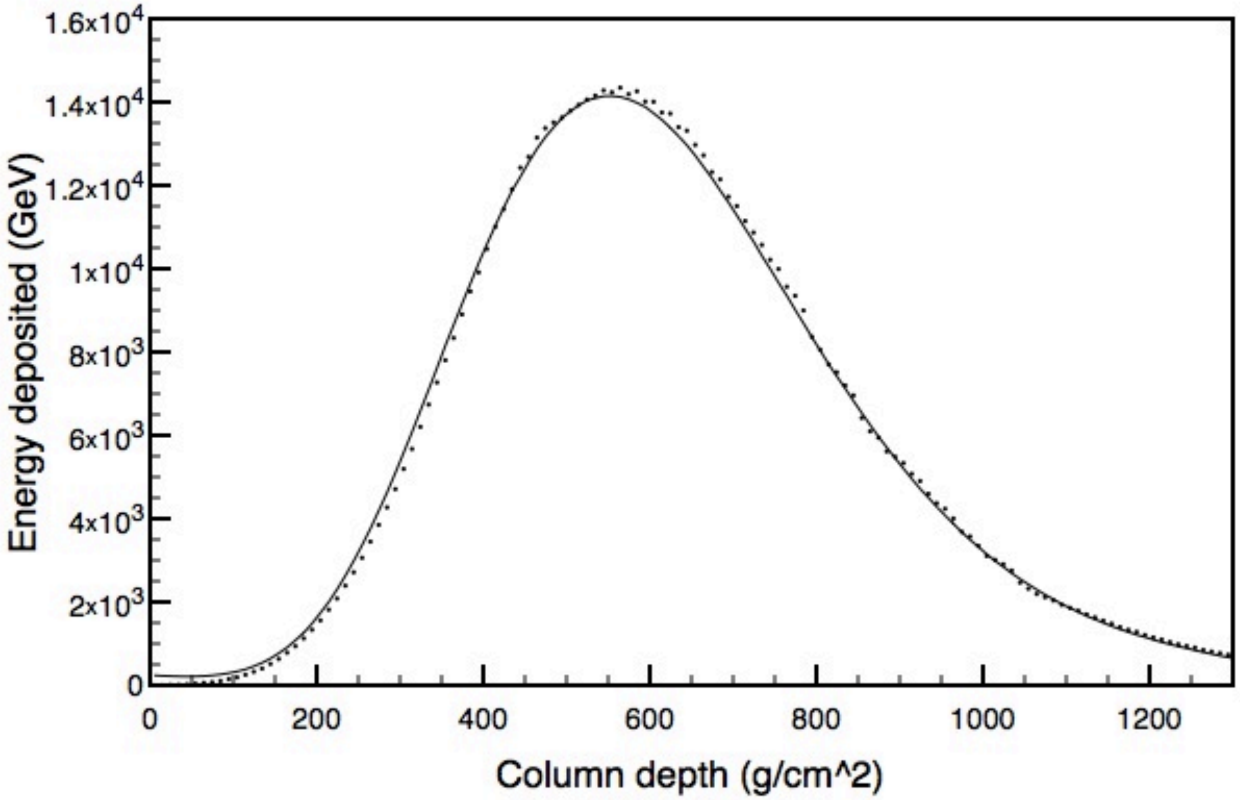
$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$
$$O_3 + O \rightarrow O_2 + O_2$$

- Harmful effects of UVB also include erythema (sunburn), skin cancer and mutations leading to other diseases.

- An increase in flux of UVB can be harmful to a variety of organisms such as phytoplankton which form the base of the food chain.

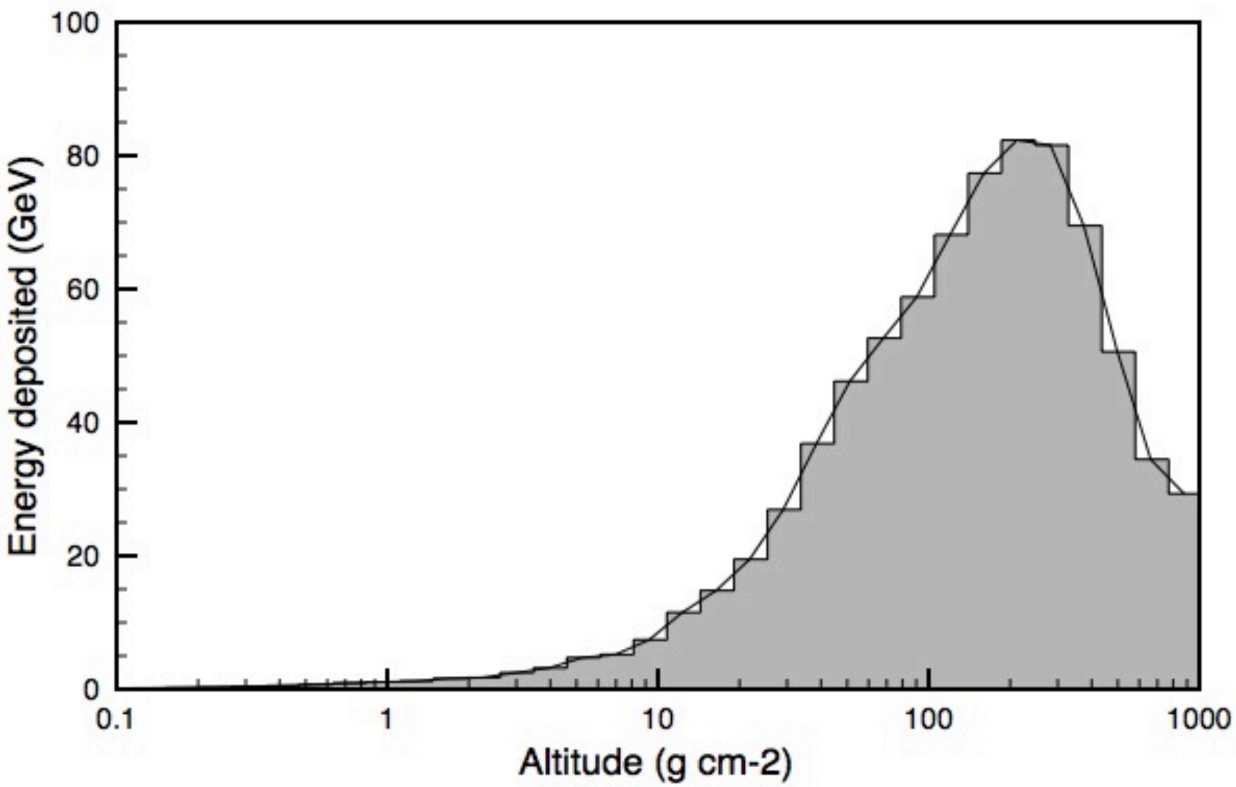
CORSIKA Simulations

~ 10^7 showers

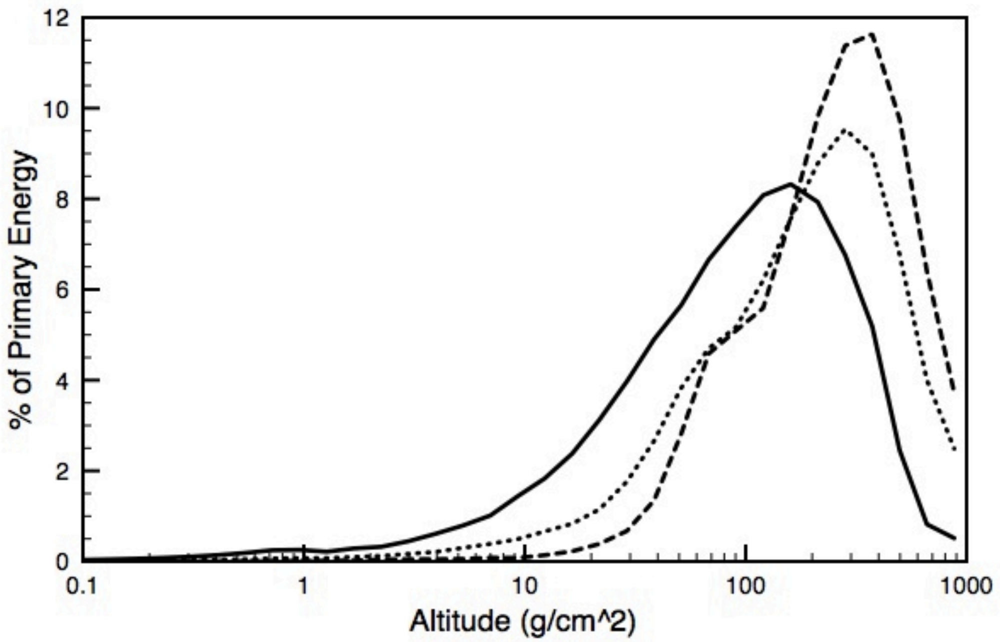


1 PeV shower: Energy deposition as a function of column depth.

Atri D., et al., "Lookup Tables to Compute High Energy Cosmic Ray Induced Atmospheric Ionization and Changes in Terrestrial Atmospheric Chemistry" (Journal of Cosmology and Astroparticle Physics, 2010).



The averaged energy deposition profile is interpolated to work as an input in the NASA GSFC 2D atmospheric modeling code.



Energy deposition due to primaries of energy 100 GeV (solid) and 10 TeV (dotted) and 1 PeV (dash). [Atri et al. 2010, JCAP]

Horizontal axis is the altitude in g cm^{-2} and the vertical axis gives the energy deposition in % of primary energy.

As expected, the peak of the energy deposition profile of the higher energy primary is deeper in the atmosphere.

- Case 1: The magnitude of the stratospheric O_3 depletion and resulting enhanced solar UVB is smaller than that experienced now from anthropogenic causes.

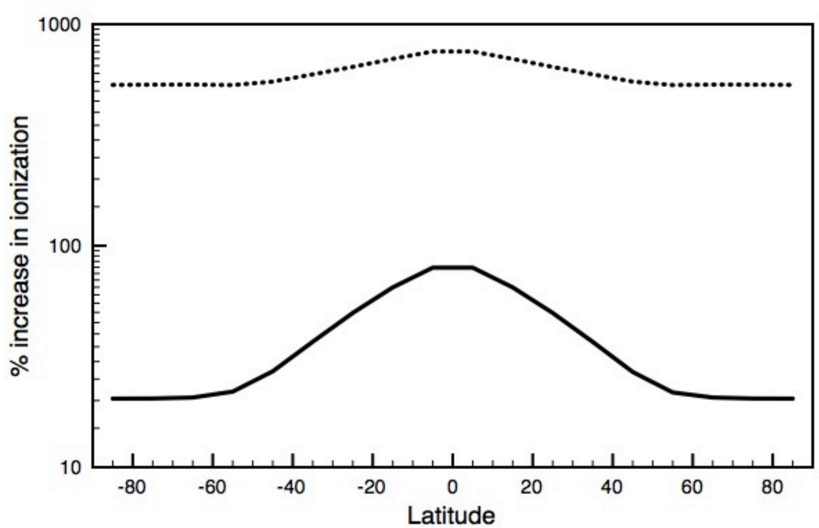
- Case 2: The effect is greater, with a globally averaged fractional depletion of about 6% in O_3 with localized maxima up to 48%.

- The reduced O_3 allows more UVB, 280-315 nm to reach the surface. The levels we find in the case 2 simulation are larger than those noted from current anthropogenic O_3 depletion (3% global average).

- UVB has a wide variety of damaging effects on organisms. (DNA gamage, skin diseases etc.)

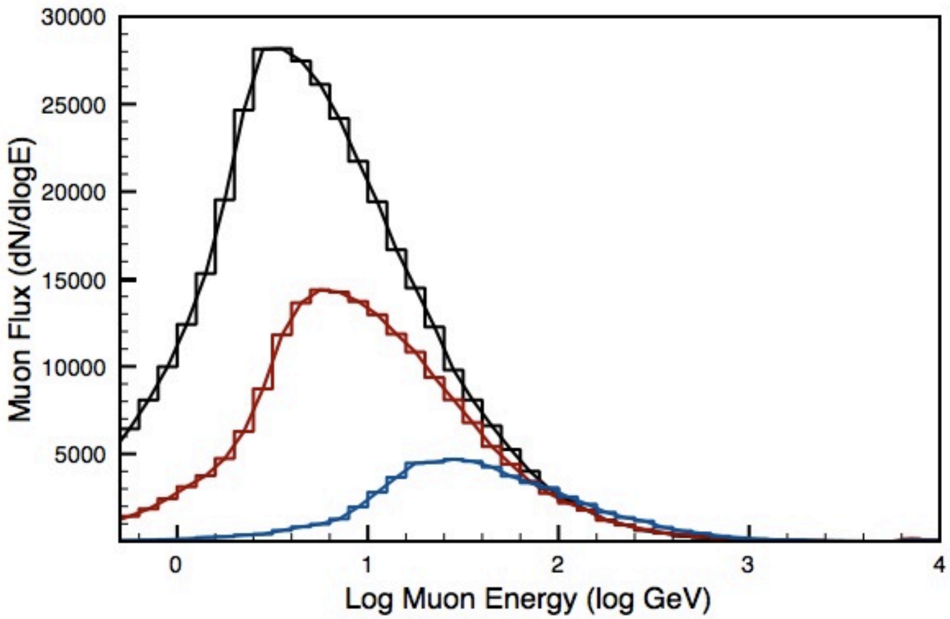
Melott, A. L. et al. "Atmospheric consequences of cosmic ray variability in the extragalactic shock model: II Revised ionization levels and their consequences" Journal of Geophysical Research, 2010.

Changes in the low altitude cloud cover?



Percent increase in atmospheric ionization for case 1 (solid) and case 2 (dotted) at 3 km altitude. The enhancement is greater at the equator than the poles because many normal cosmic rays are guided toward the poles by the geomagnetic field, while the cosmic rays in the extra-galactic model are typically too energetic to be redirected.

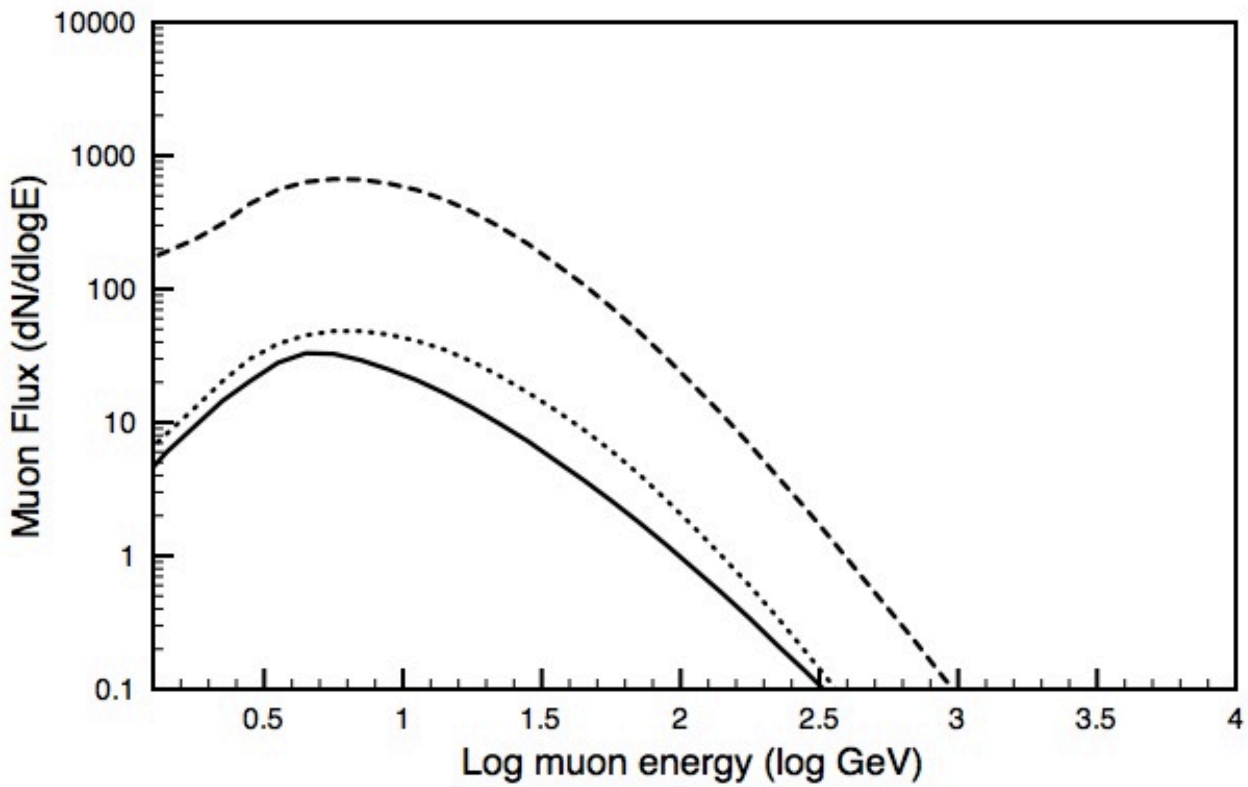
Case 1: 40 %
Case 2: x 6



Differential muon flux for 10 TeV (10000 GeV) primaries at zenith angles 5° (black), 45°(red), and 85°(cyan).

The flux goes down with increasing zenith angles.

(Atri and Melott, 2011, *Radiation Physics and Chemistry*)



Enhanced muon flux in case 1 (dots) and case 2 (dashes) compared with the normal muon flux (solid).

Atri and Melott (2011), *Geophysical Research Letters*

$$D_\mu = \int \Phi_\mu . w_{FD} . dE$$

Weighting function (W_{FD}) is independent of muon energy.

$$\frac{D_{\mu_{Enhanced}}}{D_{\mu_{Normal}}} = \frac{\phi_{Enhanced}}{\phi_{Normal}}$$

(Ferrari et al., 1997; Pelliccioni, 2000; Chen, 2006)

Natural: Cosmic Rays (10%), External dose from Uranium-Thorium series (10%), Inhaled damage to lungs (80%)

Natural radiation is 40% of the total radiation exposure on an average.

Marine Life: No lungs!
Cosmic Rays (50%), Natural radionuclides (50%)

- Case 1 (minimal) : Muon dose increase by a factor of 1.88
- Case 2 (maximal): Muon dose increase by a factor of 24.5

- Enhancement in cosmic ray dose would therefore result in about 26% increase in the total annual radiation dose on an average in case 1 and by a factor of 3.36 in case 2.

- Enhanced cosmic ray exposure provides a stress on the biosphere (Atri and Melott, 2011, Geophysical Research Letters).

We explored three terrestrial effects from enhanced cosmic ray exposure in the extragalactic shock model:

1. Damage from UVB caused by ozone depletion from cosmic ray ionization (negligible effect).
2. Potential climate change due to changes in cloud cover (no quantitative model available).
3. Radiation dose from secondary muons (primary mechanism capable of driving biodiversity decline).

1. "Lookup tables to compute high energy cosmic ray induced atmospheric ionization and changes in atmospheric chemistry".
Dimitra Atri, Adrian L. Melott, and Brian C. Thomas. *Journal of Cosmology and Astroparticle Physics*, Issue 05, DOI: 10.1088/1475- 7516/2010/05/008 (2010).

2. "Atmospheric consequences of cosmic ray variability in the extragalactic shock model II: Revised ionization levels and their consequences".
Melott, A. L., D. Atri, B. C. Thomas, M. V. Medvedev, G. W. Wilson, and M. J. Murray, *Journal of Geophysical Research - Planets*, Volume 115, Issue E8. (2010)

3. "Modeling high-energy cosmic ray induced terrestrial muon flux: A lookup table".
Dimitra Atri and Adrian L. Melott, *Radiation Physics and Chemistry,* 80, pp 701-703, DOI:10.1016/j.radphyschem.2011.02.020 (2011).

4. "Can periodicity in the low altitude cloud cover be induced by the cosmic ray variability in the extragalactic shock model?".
Dimitra Atri, Brian C. Thomas, and Adrian L. Melott, submitted (arXiv:1006.3797) (2011).

5. "Biological implications of high-energy cosmic ray induced terrestrial muon flux in the extragalactic shock model".
Dimitra Atri and Adrian L. Melott, *Geophysical Research Letters*, VOL. 38, L19203(2011).