Classroom notes for:
Radiation and Life

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Cosmic Rays (27 mrem/yr- 8% of total) (NCRP 93)
Cosmic rays consist of two types: primary and secondary.

**Primary**

- Primary cosmic rays consist primarily of high-energy protons; helium and other heavier nuclei are also components. *(Radiation and Life, Hall, p. 71)*
- Electrons, x-rays, and γ-rays are also present to a much smaller extent.
- The energies of primary cosmic rays vary from about 1 MeV to upwards of $1 \times 10^{14}$ MeV. *(Cosmic Rays, Pomerantz, p. ?)*

**Secondary**

- The “primaries” interact in the upper atmosphere to form an “air shower” of secondary particles and gamma rays.
- The “secondaries” then interact in the atmosphere themselves. This process continues in a cascade of particle creations. Collectively, all of the particles created in the atmosphere are known as secondary cosmic rays.
The highest energy cosmic ray ever recorded was detected by the Fly’s Eye detector in the western desert of Utah. The energy of the primary particle that created the shower is estimated at about 320 EeV \( (320 \times 10^{18} \text{ eV}) = 51.264 \text{ J} \).

This is roughly half of the energy of a Roger Clemens or Pedro Martinez fastball!

**mass of a Major League Baseball**

\[
5 \text{ oz} \times 28.35 \frac{\text{g}}{\text{oz}} = 141.75 \text{ g} = .14175 \text{ kg}
\]

\[
5.25 \text{ oz} \times 28.35 \frac{\text{g}}{\text{oz}} = 148.8375 \text{ g} = .1488375 \text{ kg}
\]

**velocity of a Major League fastball**

\[
95 \text{ mph} = .0263889 \text{ m/s} = 139.3333 \text{ ft/s} = 4246.88 \text{ cm/s} = 42.4688 \text{ m/s}
\]

**kinetic energy of a Major League fastball**

\[
\frac{1}{2} \times .14175 \text{ kg} \times (42.4688 \text{ m/s})^2 = 127.83 \text{ J}
\]

The origin of the particle is a mystery; some exotic production methods such as the decay of topological defects in the universe have been suggested.
Stars, including our sun, serve as sources of cosmic rays.

The sun undergoes a steady loss of mass. The corona’s high temperature gives its atoms enough energy to escape the sun’s gravity. As these atoms stream into space, they form the solar wind, a tenuous flow of mainly hydrogen and helium that sweeps across the solar system. The amount of material lost from the sun is small: less than one ten-trillionth of its mass each year. *(Explorations: An Introduction to Astronomy, Arny, p. 304)*

- The corona is the sun’s outer atmosphere.
- This spray of superhot ionized gas, known as plasma, blows across interplanetary space in what is termed the solar wind. *(National Geographic, November 2001, p. 54)*

The Apollo 11 astronauts reported seeing streaks of light when they closed their eyes; this effect was caused by cosmic rays passing directly through the astronauts’ eyes and causing direct effects on their retinas.
Cosmic ray activity peaks when solar flare activity peaks.

Sunspots give birth to solar flares, brief but bright eruptions of hot gas in the chromosphere. (Explorations: An Introduction to Astronomy, Arny, p. 301)

The chromosphere is the sun’s lower atmosphere.

Sunspot and flare activity change from year to year in what is called the solar cycle. The numbers clearly rise and fall approximately every 11 years. (Explorations: An Introduction to Astronomy, Arny, p. 306)

Because the (sun’s magnetic) field and gas are tightly connected together, differential rotation causes gas at the equator, which is moving faster than the gas at the poles, to drag the magnetic field with it so that a field, initially straight north to south, is wound into two subsurface loops. As the loops are wound tighter, they develop kinks, as when you twist a rubber band too tight. The cycle ends when the field twists too “tightly” and collapses, and the process repeats.

(Explorations: An Introduction to Astronomy, Arny, p. 307)
The sunspots form when the kinks rise to the sun’s surface and break through the photosphere. Here, the field slows the outward flow of heat, making the surface cooler and darker than in surrounding areas and thereby creating sunspots. 

(Explorations: An Introduction to Astronomy, Arny, p. 307)

– The photosphere is the sun’s visible surface \((T = 5780 \, \text{K})\).

(Explorations: An Introduction to Astronomy, Arny, p. 288)

– The magnetic field can be twisted only so far before it suddenly readjusts, whipping the gas in its vicinity into a new configuration. The sudden motion heats the gas, and it expands explosively. Some gas may even escape from the sun and shoot across the inner solar system to stream down on the earth. (Explorations: An Introduction to Astronomy, Arny, p. 302)

– Dose rates due to flares peak at a rate of a few rem/hr outside the atmosphere.
On the earth, irradiation by cosmic rays varies with location

*Latitude*

- Dose increases with increasing latitude (approaching poles).
- The earth’s magnetic field deflects charged particles away from the equator towards the magnetic poles.

Thus, more cosmic rays will impinge upon the atmosphere at the highest latitudes (towards the poles) than at the equator. The charged particles that get trapped in the “magnetotail,” which may stretch millions of miles, can be sent hurtling back toward Earth. Then, in a variety of possible ways not yet fully understood, some eventually rain down into the upper atmosphere over the polar regions- the places where our protective magnetic envelope is most open to space. (*National Geographic*, November 2001, p. 54)

At the earth’s surface, this variation with latitude is significant:

- 35 mrem/yr at the equator, and
- 50 mrem/yr at 50 degrees latitude (London, NY, Tokyo).

(*Radiation and Life*, Hall, p. 63)
The particles can spend a significant amount of time in the field before interacting with the atmosphere; these particles comprise the Van Allen radiation belt (Dose rates are as high as 10 rems/hr in the belt).

Incidentally, cosmic rays interacting in the atmosphere produce the aurora borealis (the northern lights) and the aurora australis (the southern lights).  

– Aurora is Latin for “dawn”. (National Geographic, November 2001, p. 50)
– There are two great ovals of auroral activity encircling the geomagnetic poles- one for the aurora borealis in the Northern Hemisphere, one for the mirroring aurora australis in the Southern. These typically bulge farther toward the Equator on Earth’s night side and change shape a bit in the course of a single day. During a big aurora they may move even farther, giving people beyond the normal limits a glimpse of the lights. (National Geographic, November 2001, p. 54)

Auroral light comes largely from electrons hitting oxygen and nitrogen atoms and molecules in the upper atmosphere, the same phenomenon that produces the glow in a neon lighting tube. Essentially it is the light emitted by the de-exciting electrons in the atoms.
Altitude

Dose increases with increasing altitude, because at high altitudes, there’s less atmosphere to act as a shield.

Rates are:
- 90 mrem/yr in Denver,
- 300 mrem/yr at highest inhabited areas, and
- 800 mrem/yr at peak of Mt. Everest. *(Radiation and Life, Hall, p. 64)*

The worldwide average over both altitude and latitude is about 50 mrem/yr *(Radiation and Life, Hall, p. 65)*

Occupations requiring extended stays at the highest altitudes have the highest occupational dose rates of any profession.
- 500-900 mrem/year for subsonic aircraft crew,
- 800-1700 mrem/year for supersonic aircraft crew, and
- 1700-14,400 mrem/year for astronauts in earth orbit *(Heath Physics, November 2000, p. ?)*

These yearly occupational doses do not contribute significantly to the U.S. annual average for cosmic rays because the target populations are so small (in fact, occupational doses are actually included in the final category “Other”)*
Terrestrial Sources (28 mrem/yr- 8% of total)  
(NCRP 93)

The earth’s crust contains radioactive elements that contribute to terrestrial dose.

- Uranium-238 and thorium-232 are still present from formation of earth.
- $t_{\frac{1}{2}} = 4.51 \times 10^9$ for U-238 and $t_{\frac{1}{2}} = 1.41 \times 10^{10}$ for Th-232

They can be found in all soil, but tend to have higher abundances in granite. They produce many progeny as part of their long decay series.

The following levels of natural radioactivity are representative of the levels typically found in a region of soil one-mile long by one-mile wide by one-foot deep.

- uranium 0.8 Ci
- thorium 1.4 Ci
- potassium-40 13 Ci
- radium 1.7 Ci
- radon 0.2 Ci  
It is the progeny of U-238 and Th-232 that contribute most to the dose.

- Many of the progeny emit gamma-rays of sufficient energy to cause an external dose.
- Can receive dose indoors if concrete was used as a building material (concrete is made from gravel and cement).
- The average annual terrestrial dose in The Vatican is 800 mrem/yr. ([http://www.em.doe.gov](http://www.em.doe.gov))

The average annual dose due to terrestrial sources varies with location.

Individuals in the Gulf and Atlantic Coastal states receive about 16 mrem/yr.

Individuals in Arizona, Colorado, New Mexico, or Utah receive about 63 mrem/yr. ([Chemistry in the Community](http://www.em.doe.gov) 4th Ed., American Chemical Society, p. 430)

The overall U.S. yearly average doses are as follows.

- outdoors: 45-130 mrem/yr
- indoors: 29-90 mrem/yr ([Radiation and Life](http://www.em.doe.gov), Hall, p. 65)
Radon, even though it is part of the U-238 decay series, is excluded from this category. In 1984, it was included, and was only believed to cause 50 lung cancer deaths per year. *(Radiation and Life, Hall, p. 66)*

**Sources Internal to the Human Body (39 mrem/yr- 11% of total) (NCRP 93)**

There are trace amounts of naturally occurring radioisotopes in the environment that will be taken in by organisms.

- For instance, all organisms contain carbon (C) and potassium (K), and therefore they all contain trace amounts of radioactive C-14 and K-40.
- Recall that C-14 is not left over from the earth’s creation; it is produced naturally in the upper atmosphere as a result of nuclear reactions induced by cosmic radiation. *(Radiation Safety and Control, Volume 2, French and Skrable, p. 10)*

K-40, however, with a $1.27 \times 10^9$ year half-life, is left over from the earth’s formation.

Potassium-40, with an energetic 1.46 MeV $\gamma$-ray, is the largest contributor to internal dose.
Other contributors include the following:

<table>
<thead>
<tr>
<th>organ</th>
<th>radioisotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>thyroid</td>
<td>iodine-131</td>
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<tr>
<td>lungs</td>
<td>radon-222</td>
</tr>
<tr>
<td></td>
<td>uranium-238</td>
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<tr>
<td></td>
<td>plutonium-239</td>
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<td></td>
<td>krypton-85</td>
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<td>muscles</td>
<td>potassium-40</td>
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<tr>
<td></td>
<td>strontium-90</td>
</tr>
<tr>
<td></td>
<td>phosphorus-32</td>
</tr>
<tr>
<td></td>
<td>carbon-14 (.4 μCi total in body)</td>
</tr>
</tbody>
</table>

(Chemistry in the Community 4th Ed., American Chemical Society, p. 429)
High Natural Radiation Areas

- There are five major inhabited areas worldwide with high levels of natural ("background") radiation: Brazil, France, India, Niue Island, and Egypt. (Radiation and Life, Hall, p. 67).

- For instance, in Kerala and Madras States of India, a coastal region 200 kilometers long and several hundred meters wide lies above an area of intense radioactivity, such that a population of over 100,000 people receive an annual dose-rate which averages 1,300 mrem per year. This is the highest level of natural background radiation to which any human beings are exposed. (Radiation and Life, Hall, p. 68)

- Note that (http://www.em.doe.gov quotes an average annual dose of 400 mrem/yr for the coast of Kerala, India).
The people who live in these areas of the world where the natural radiation is much higher than average have been carefully studied to see whether genetic anomalies, or cancer, are more prevalent than usual. So far, it has not been possible to establish any connection between the level of background radiation and an increase in biological disorders. It would be foolish, however, to derive too much comfort from this negative result, since the few studies that have been made were beset with difficulties. To begin with, the number of people who live in these areas of high natural background is relatively small. A more serious difficulty is that, as a rule, the people exposed differ from the majority of people on earth in such basic things as diet and social habits as well as ethnic origins. They also tend to live in small closed communities, and suffer from the increased congenital anomalies associated with inbreeding.
Nevertheless, in spite of the obvious difficulties involved, it is a fact that no elevated levels of genetic anomalies or cancer incidence can be linked with high background radiation levels, even though some people live in areas receiving ten time the average radiation doses. This has an important practical consequence. It is justification for believing that man-made radiation in amounts comparable to background is unlikely to produce a detectable number of detrimental biological changes in the world’s population. This is a compelling argument.

If by living in the United States and receiving a man-made dose from nuclear power reactors and diagnostic x-rays, one does not receive a dose which is more than that received naturally by millions of people in France or hundreds of thousands of people in India, then it is difficult to imagine that any disastrous biological consequence will result. (Radiation and Life, Hall, pp. 68-69)
The Oklo Natural Reactor

In 1972, a natural nuclear reactor was found in a western Africa in the Republic of Gabon, at Oklo. While the reactor was critical, approximately 1.7 billion years ago, it released 15,000 megawatt-years of energy by consuming six tons of uranium. It operated over several hundred thousand years at low power.

Samples of U-235 from Oklo were found with natural enrichments of .7171%; later, samples were found more depleted, down to .44%. This difference could only be explained if some of the U-235 had been used up in a fission reaction (at the time of the reactor, enrichment was 3%). Upon further investigation, abnormally high amounts of fission products were found in six separate reactor zones.

The Oklo Natural Reactor

Oklo Mine Site in Oklo, Gabon
Photo courtesy of Andreas Mittler
http://www.ans.org/pi,np,oklo/