Outline

- What are Cosmic Rays?
- What are Muons?
- Radiation exposure due to cosmic rays
- Detecting Cosmic Rays and other radiation
- Cosmic ray muon intensity and the weather

BC: Johnny Hart
Viktor Hess: 1911-1913 work

- Electroscopes...
- Natural radiation in the earth: was expect to to lessen at heights
- Eiffel Tower test: nope...
- Viktor Hess’ daring balloon flights with electroscopes
  - Up to 5.3 km!
  - Intensity more than doubles
- Some radiation is of extraterrestrial origin!
- Nobel Prize 1936
Cosmic ray rate (intensity) vs. altitude

Variation of cosmic rays with altitude

Counting rate (coincidences/min)

Altitude in km

Atmospheric pressure in mmHg
Yes, but what is this radiation?

- **At the top of the atmosphere:**
  - Protons
  - Anti-particles
  - AMS / Space Station

- **In between**
  - Particle “showers”

- **At ground level**
  - **Muons** ← our main topic!
  - Neutrons
“Primary” Cosmic Rays

• **Mostly** Protons: stable, live forever
• Bits of lots of other stuff: electrons, helium nuclei... iron nuclei, anti-particles...
• Alpha Magnetic Spectrometer (AMS-02) on International Space Station
  – Taking a census of everything arriving at earth
Where do cosmic rays come from?

- We don’t know.
- Not the sun.
- Galactic magnetic fields scramble paths
- Solar wind particles: Aurora
- Cosmic rays: ongoing mystery
Role of the Sun in Aurorae

variable solar wind can give some radiation belt particles enough energy to spiral into atmosphere and create aurorae

Most solar wind particles deflected on past planet but a few leak into magnetosphere to get trapped in radiation belts
Indirect Role of the Sun on Cosmic Rays
Cosmic Ray Showers

- High energy cosmic rays cause a cascade of particle production in the atmosphere.

- **Muons** have the most bang for (energy) buck: penetrate to the surface (and below).

- Rate: 180 particles/m²/sec

---

**KEY**

- P: Proton
- n: Neutron
- π: Pion
- e: Electron
- μ: Muon
- γ: Photon
The Muon: “Who ordered that?”

• Very much like a “heavy electron”:
  – Charged “+” or “-”
  – 206 times more massive than the electron 🙈
  – Unstable: decays in 2.2 microseconds to an electron or positron and two neutrinos
  – A type of “ionizing radiation” because it can rip electrons off atoms
Deep Underground Muons:

- Go deep to escape cosmic ray muons
- See instead muons created by neutrinos
# Human Exposure to Ionizing Radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>Place</th>
<th>Exposure</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic Rays</td>
<td>Sea Level</td>
<td>26</td>
<td>milli-rem / year</td>
</tr>
<tr>
<td></td>
<td>Pittsburgh</td>
<td>30</td>
<td>“</td>
</tr>
<tr>
<td></td>
<td>Denver</td>
<td>50</td>
<td>“</td>
</tr>
<tr>
<td>Ground</td>
<td></td>
<td>35</td>
<td>“</td>
</tr>
<tr>
<td>Food ($^{14}$C, $^{40}$K)</td>
<td></td>
<td>40</td>
<td>“</td>
</tr>
<tr>
<td>Air (Radon)</td>
<td></td>
<td>200</td>
<td>“</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>~ 300</td>
<td>“</td>
</tr>
<tr>
<td>Workplace Limit (US)</td>
<td></td>
<td>5,000</td>
<td>“</td>
</tr>
<tr>
<td>Air travel / hour</td>
<td></td>
<td>0.5 / hour</td>
<td>milli-rem</td>
</tr>
<tr>
<td>Chest X-ray</td>
<td></td>
<td>10</td>
<td>“</td>
</tr>
<tr>
<td>Chest CT scan</td>
<td></td>
<td>700</td>
<td>“</td>
</tr>
<tr>
<td>Dental X-ray</td>
<td></td>
<td>~ 1</td>
<td>“</td>
</tr>
<tr>
<td>MRI scan (not ionizing!)</td>
<td></td>
<td>0</td>
<td>“</td>
</tr>
<tr>
<td>½ pack of cig’s/day</td>
<td></td>
<td>18</td>
<td>“</td>
</tr>
<tr>
<td>Lethal Dose</td>
<td>Hiroshima, Nagasaki</td>
<td>450,000</td>
<td>mrem all at once</td>
</tr>
</tbody>
</table>
Does the intensity of cosmic ray muons depend on the weather?

Space conditions: magnetosphere effects

Atmospheric conditions: pressure, temperature, humidity, height...
Undergraduate Research Project

What is the correlation between atmospheric conditions \{Pressure, Temperature, and “Height”\} with the rate of muons at ground level?
Detectors: Geiger Counter

Spread of avalanches in a Geiger-Muller tube

Key:
- Ionisation event
- Ionising electron path
- Liberated electron path
- UV photon path & collision

Not to scale
Detectors: Scintillator & Photomultiplier

(Method 2)
Experimental Setup

- 5" Photomultiplier Tube
- 12" Scintillator Block
- PMT A
- Light Guide (Lucite)
- PMT B
- Aluminum Box
- Steel Shell
- Base
Experimental Setup
Weather Conditions

• Allegheny County airport aviation weather
  – Local barometric pressure (surface)

• NOAA/IGRA weather balloon data
  – Height of atmosphere at 10 kPa pressure
  – Temperature at 10 kPa pressure

• Space weather
  – We had no data source!
Muon Rate Correlations with Weather?

• Linear Regression Model:

\[
\frac{\Phi - \langle \Phi \rangle}{\langle \Phi \rangle} = \alpha \left( \frac{P - \langle P \rangle}{\langle P \rangle} \right) + \beta \left( \frac{H - \langle H \rangle}{\langle H \rangle} \right) + \gamma \left( \frac{T - \langle T \rangle}{\langle T \rangle} \right)
\]

• Raw Data:
  – 5 months of averaged hourly readings of P, T, H, and Φ
    • Surface pressure (\(~ 101\) kPa)
    • Temperature at 10 kPa pressure (\(~ 207\) K)
    • Height of atmosphere at 10 kPa level (\(~ 16.6\) km up)
    • Muon flux

• Two categories of muons:
  – Slow muons stop in scintillator (kinetic energy < 150 MeV)
  – Fast “in-flight” muons barrel right through the detector
Mean Muon Lifetime

For stopping muons

Number of Events

Mean Muon Life: The mean muon life is 2.2 microseconds.

Decay Time (μs)

Straight line on a logarithmic scale

Mean lifetime is 2.2 microseconds
Raw Data: 5 months of readings

7 weeks of smooth, “clean” data

Effect of space weather:
- Forbush fluctuations
- blame the sun and Earth’s magnetosphere
For stopping muons

Nice fit of model to 7 weeks of “clean” data!
For in-flight muons

Effect of space weather: Forbush fluctuations
- blame the sun and Earth’s magnetosphere
For in-flight muons

Very good fit of model to 7 weeks of “clean” data!

Weather affects stopping muons more strongly
Experimental Results

Pressure rises $\rightarrow$ Muon rate falls

Atmosphere Expands $\rightarrow$ Muon rate falls

Atmosphere Warms $\rightarrow$ Muon rate rises

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Eq. 1</th>
<th>Stopped Muons</th>
<th>Total Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>$\alpha$</td>
<td>$-3.2 \pm 0.5$</td>
<td>$-1.94 \pm 0.10$</td>
</tr>
<tr>
<td>Altitude</td>
<td>$\beta$</td>
<td>$-2.7 \pm 0.9$</td>
<td>$-0.8 \pm 0.2$</td>
</tr>
<tr>
<td>Temperature</td>
<td>$\gamma$</td>
<td>$+0.35 \pm 0.17$</td>
<td>$+0.08 \pm 0.04$</td>
</tr>
</tbody>
</table>

$\chi^2_{\nu} = 1.07$  \hspace{1cm} $\chi^2_{\nu} = 1.09$
Re-cap / Summary

• Cosmic rays are messengers from the galaxy and beyond... not from our sun; mostly protons

• Cosmic rays at Earth’s surface are mainly muons from atmospheric “showers”

• Ionizing radiation due to cosmics: evidently we are evolved to tolerate it

• Muon intensity depends on atmospheric and space weather conditions: more-so for lowest energy muons
Supplemental Slides
## Units for Ionizing Radiation

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversions</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>bequerel</td>
<td>1 Bq = 1 decay / second</td>
<td>Activity</td>
</tr>
<tr>
<td>curie</td>
<td>1 Ci = $3.7 \times 10^{10}$ decays/sec</td>
<td></td>
</tr>
<tr>
<td>rad</td>
<td>100 rad = 1 Gy</td>
<td>Absorbed dose (energy / mass)</td>
</tr>
<tr>
<td>gray</td>
<td>1 Gy = 1 Joule/kg</td>
<td></td>
</tr>
<tr>
<td>rem</td>
<td>“Röntgen equivalent in man”</td>
<td>Equivalent dose (energy / mass)</td>
</tr>
<tr>
<td></td>
<td>(1 R of X-rays ~ 1 rem in tissue)</td>
<td></td>
</tr>
<tr>
<td>sievert</td>
<td>1 Sv = 100 rem</td>
<td></td>
</tr>
<tr>
<td>röntgen</td>
<td>1 Coulomb / kg of air = 3880 R</td>
<td>Exposure (charge / mass)</td>
</tr>
</tbody>
</table>