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Outline:

- History of cosmic rays (CRs)
- What are cosmic rays anyway? (composition, rates)
- You’ve got to be kidding me, right? (sources)
- How do we know what we know? (detectors)
- Gamma–Ray Astronomy
- Neutrino Astronomy
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History:
- Prehistory (pre-WWII)
  - (1912) – Victor Hess used "Electroscope" to discover that CRs come from space, not earth

- Took "scope" in balloon flights up to 17500 ft.
- Found that rate of discharge of "scope" increased with increasing altitude.

- Thus CRs were:
  - Charged (mainly)
  - Coming from outer space

"father of cosmic-rays"
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How an electroscope functions:

- Charged particle traverses chamber
- Freed electrons neutralize positive charge on deflection arm
- Rate of discharge of scope is proportional to CR rate

Uncharged

Charged
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History:

- Prehistory (pre-WWII)
  - (1912) – Victor Hess used "Electroscope" to discover that CRs come from space, not earth
- 1930–40’s – Compton, Rossi, Vallarta found that rate of CRs depended on latitude on earth ➔ + Charged particles
- 1932 – Carl Anderson discovers antimatter (positron) in his "cloud chamber"
- 1937 – Seth Neddermeyer & Carl Anderson discover the muon (second of a series of subatomic particles discovered using CRs)
- 1938 – Pierre Auger discovers CR airshowers
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Example of CR interacting in an emulsion
History (continued):
- Post–WWII (better balloons → Primary CRs)
  - 1946–1954 Use of emulsions, cloud chambers, and counter telescopes allows the determination of cosmic ray composition
    - Completely ionized H, He, Li, Be, B, and heavier nuclei as well as elementary particles: p, n, e⁻, e⁺
    - Could reach up to a few GeV
- 1949 – Enrico Fermi proposes stochastic acceleration of CRs
- 1954–Present – Air shower arrays at MIT, Japan, Chacaltaya, India, Soviet Union, Australia extend energy reach to > PeV
- Present:
  - Satellites such as HEAφ, PROTON, ... provide data supporting "Leaky Box Model of CRs"
  - Underground experiments like KGF, Homestake, MACRO, IMB discover, atmospheric and CR neutrinos
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- What are CRs anyway?
  - As stated, they are high energy subatomic particles
  - They have rained down on earth in an ~ constant, isotropic, flux for millions of years
  - Example:
    - You have just volunteered to be test subject in CR experiment
    - You are put into space with no CR shielding
    - Compute your radiation dosage (E deposited per gram):
      - Energetic nuclear CR rate above atmosphere:

\[
CR_{\text{rate}} \approx \frac{1 \text{ particle}}{cm^2 \text{ s sr}}
\]

# traversing from all directions: \[
\frac{6 \text{ part}}{s \text{ cm}^2}
\]
Example (continued):
- Your crossection: \(1.8\text{m}(\text{height}) \times 0.5\text{m}(\text{width}) = 9000 \text{ cm}^2\)

- Rate of particles entering you:
  \(9000 \text{ cm}^2 \times \frac{6 \text{ part}}{s \text{ cm}^2} = 54,000 \text{ part/s}\)

- Typical penetration depth: \(\sim 10\text{cm}\)

- Energy deposited per particle: \(\sim 2 \text{ MeV/cm} \Rightarrow 20 \text{ MeV/part}\)

- Total deposited energy per second:
  \[
  E_{\text{dep}} = 20 \frac{\text{MeV}}{\text{part}} \times 54,000 \frac{\text{part}}{s} \approx 10^6 \text{ MeV/s}
  \approx 1.6 \times 10^{-6} \text{ ergs/s}
  \]

\(1 \text{ eV} = 1.6 \times 10^{-12} \text{ ergs}\)
Example (continued):

- Compare this to the "Radiation dosage recommendation per year"
- First need energy deposited per gram:

\[
1 \text{ Rad} = 6 \times 10^7 \frac{\text{MeV}}{\text{g}}
\]

\[
\frac{E_{\text{dep}}}{\text{g} \cdot \text{s}} = \frac{10^6 \text{MeV/s}}{7 \times 10^4 \text{g}} = \frac{14 \text{MeV}}{\text{g} \cdot \text{s}} = 2.3 \times 10^{-6} \text{Rad/s}
\]

- Dosage in one year:

\[
\text{Dosage} = \omega_R \times \text{rate} \times \text{time} = 5 \times 2.3 \times 10^{-6} \times 3.1 \times 10^7
\]

\[
= 350 \text{ Rad/yr}
\]

- Max recommended dosage per year: ~ 10 Rad/yr

\[
\omega_R \equiv \text{radiation weighting factor} \approx 5
\]
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Luckily for us (except perhaps for high energy astronomers) most of the CRs are absorbed by the atmosphere such that CR flux at sea level is $\sim 300/(m^2s)$
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- So What are CRs?
- Better yet: Why study CRs at all?
  - They contribute significantly to the energetics of the galaxy
  - They are messengers for cosmogenic processes which produce the elements of the periodic table
  - Solar CRs from flares and coronal mass ejections (CMEs) influence our ionosphere and can have serious consequences to our satellite communications
  - The highest energy CRs above $10^{20}$ eV are not understood have give us a glimpse into extremely energetic phenomena which we can’t study on earth
  - They (with $\gamma$–rays and neutrinos) aid us in studying astrophysical objects such as Active Galactic Nuclei (AGN), supernova explosions, coalascing black holes & neutron stars, and perhaps Gamma Ray Bursts
CR properties:
- "All particle" spectrum (flux vs. energy) (right)
- CR Primary composition (below)
Where do they come from and how do they get here?

- Sources of CRs
  - Sun and other stars. Particles emitted in solar flares or CMEs mainly protons and nuclei up to iron. E up to ~ 50 GeV?
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Cosmic rays include nucleosynthetic products from other regions of our galaxy.

Massive star near the end of its lifetime has an onion-like structure just prior to exploding as a supernova.

Nucleus burning occurs at the boundaries between zones.

Example of nuclear reactions that build neutron-rich isotopes.

H, He

He, N
HeC, 22Ne
O, C
O, Ne, Mg
S, S

Fe, Ni
Core

Red Giant
Where do they come from and how do they get here?

Sources of CRs

- Sun and other stars. Particles emitted in solar flares or CMEs mainly protons and nuclei up to iron. \( E \text{ up to } \sim 50 \text{ GeV?} \)
- Supernova: Stellar explosions of massive stars where matter is ejected into surrounding region and is swept up by outward propagating shocks. \( E \text{ up to } \sim 100 \text{ TeV} \)
- Nuclei may be accelerated via Fermi Acceleration and/or blast wave acceleration

Both transits boost CRs energy

Predicts "power–law" spectrum of \( \sim \) right power
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- Pulsar lighthouse model:
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Where do they come from and how do they get here?

- **Sources of CRs**
  - Sun and other stars. Particles emitted in solar flares or CMEs mainly protons and nuclei up to iron. *E up to ~ 50 GeV?*
  - Supernova: Stellar explosions of massive stars where matter is ejected into surrounding region and is swept up by outward propagating shocks. *E up to ~ 100 TeV*
  - Nuclei may be accelerated via Fermi Acceleration and/or blast wave acceleration
  - Pulsars (rotating neutron stars)
  - Active Galactic Nuclei (AGN)
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Site of CR acceleration?

Chandra X-Ray image of 3C273 AGN

AGN Model
X-rays from deep within AGN show two largely different regions near black hole. Jets along magnetic axis is where CRs are thought to be accelerated.
Okay, so how do CRs get to us from these supposed sources?
- CR propagation
  - Near earth, magnetosphere deflects CRs with $E < 5$ GeV
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- False color image of the charged plasma from the solar wind trapped by the earth’s magnetosphere
  - IMAGE spacecraft, EUV.
  - Earth is in the center, viewed above N. pole
  - Sun is out of picture toward the upper right
  - Faint central ring is Aurora
Okay, so how do CRs get to us from these supposed sources?

CR propagation (continued)

At a few solar system radii scale there is a corresponding magnetic structure called the Heliosphere which effects CR propagation into/out of the solar system.
Okay, so how do CRs get to us from these supposed sources?

- CR propagation (continued)
  - At Galactic scales, semi–ordered galactic magnetic fields (~ 3 μG) influence the propagation of CRs.
  - Below ~ 1 PeV, CRs are "trapped" in galaxy and slowing leak out (Leaky Box Model)

- Use ratio of unstable to stable isotopes (i.e. $^{10}$Be)

- Escape time depends on $R$ (rigidity) but on scale of $2 \times 10^7$ years

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How do we detect CRs?
- Low energies ( < 1 TeV): Satellites & Balloons

http://atic.phys.lsu.edu/aticweb
http://marge.phys.washington.edu/jacee

ATIC: Advanced Think Ionization Calorimeter

(show movie!)

JACEE: Japanese–American Collaborative Emulsion Experiment
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Schematic of JACEE Emulsion Detector:
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- ACE: Advanced Composition Experiment (satellite)
  - Launched 8/5/97
  - Has multiple instruments

http://www.srl.caltech.edu/ACE
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- One example ACE instrument:
  - CRIS (Cosmic Ray Isotope Spectrometer)
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- What CRIS hopes to measure: various isotopes of elements
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- What if CR rates are too low to be seen by detectors on balloons or satellites?
- Detect them through are showers!
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- CR airshower development:
  - If energy too low, no particles make it to the ground (but Cherenkov light can)
  - All particles travel ~ c
  - Secondaries form a thin "pancake"

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**Diagram:**
- 1 TeV cosmic ray
- 1000 TeV cosmic ray

**Legend:**
- p = proton
- μ = muon
- π = pion
- ν = neutrino
- e^+ = electron
- e^- = positron
- γ = photon

**Telescopes:**
- Air Cherenkov Telescope
- Airshower Array
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γ-ray Astronomy

- Example Air Cherenkov Telescope:
  - Whipple ACT on MT Hopkins, Arizona
  - 10m multisegmented mirror
  - Light is focused onto "camera" of PMTs
  - Energy threshold: ~ 300 GeV
  - Objects seen:
    - Crab Nebula
    - 4 AGN

http://egret.sao.arizona.edu

Are γ-rays tracers for cosmic rays?
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Example Airshower Array:
- KASCADE (Karlsruhe Shower Core and Array Detector)
- Karlsruhe, Germany
- 252 detectors
- 40,000 m² area
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- Example Airshower Array:
  - KASCADE goals
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Example airshower array for γ-ray astronomy:

- Milagro
  - Located at 8600’ in Jemez Mtns in NM.
  - Detects CRs with
    500 GeV < E < 100 TeV
  - Detects CRs at ~ 1800 per sec.
    24/7/365 day per year (~ 95%)
  - 723 8” PMTs and 176 8’ water Cherenkov tanks
  - Has detected TeV level photons from:
    - Crab Nebula, Mrk501 & Mrk421 (AGN)
    - And perhaps 1 Gamma Ray Burst (GRB)

http://www.lanl.gov/milagro
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The Milagro Pond:
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- The Full Milagro Detector:
  - 176 8’ x 4’ deep water tanks

200 m

Pond

Shoup – 37
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How Milagro determines CR direction:

(angle formula)
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- How do we detect the highest energy CRs? (> $10^{18}$ eV)
- Pierre Auger Project:
  - Located in Malargue, Argentina
  - 1600 water Cherenkov tanks, 1.5 km apart 3000 km$^2$!
  - Air flurescence telescope(s)
  - Will detect CRs with $E > 10^{18}$ eV up to highest energies (> $10^{20}$)
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- Another highest energy CR array closer to home:
  - CHICOS: California HIgh school Cosmic-ray ObServatory
  - CalTech, Cal State
  - Northridge, UCI, local high schools
  - 23 sites deployed
  - Possibility for 1800?
  - Have 2 detectors per school plus computer & electronics
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- What each school site consists of:

- What rates we hope to reach:

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**Table 1. Estimated aperture and event rates for three different threshold energies for an 80 site CHICOS array.**

<table>
<thead>
<tr>
<th>Energy Threshold</th>
<th>Aperture</th>
<th>Events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{18}$ eV</td>
<td>10 km$^2$-sr</td>
<td>600</td>
</tr>
<tr>
<td>$10^{19}$ eV</td>
<td>200 km$^2$-sr</td>
<td>120</td>
</tr>
<tr>
<td>$10^{20}$ eV</td>
<td>500 km$^2$-sr</td>
<td>3</td>
</tr>
</tbody>
</table>
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What about \textit{neutrinos}?

- Two categories:
  - Atmospheric: Produced in CR airshowers
    - \textbf{Problem: ratio of }$\nu_e$ to $\nu_\mu$ \textit{is wrong!}
  - Astrophysical
    - Solar – tell us about nuclear fusion in sun’s core
      - \textbf{Problem: see too few of them (by factor of $\sim 2$)}
    - Galactic and Extragalactic
      - From sources like Supernova, SNR?, Pulsars?, AGN?

Detectors:
- Many but let’s talk about:
  - Super–Kamiokande
  - Amanda / Ice–cubed
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- First SuperK:
  - 50,000 ton tank of purified water, 1km below ground
  - 11,146 50 cm pmts on inside
  - Several thousand 8" pmts on outside

Cherenkov cone

Muon
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- First SuperK (continued):
  - Neutrino Oscillations:
    - Concept of one neutrino type spontaneously converting into another
    - Used to explain "missing solar and atmospheric neutrinos"

- Two requirements:
  - Mixing between neutrino mass and weak interaction eigenstates:
    \[
    \begin{pmatrix}
      \nu_\mu \\
      \nu_\tau \\
      \nu_e
    \end{pmatrix}
    =
    \begin{pmatrix}
      \cos \theta & -\sin \theta \\
      \sin \theta & \cos \theta
    \end{pmatrix}
    \begin{pmatrix}
      \nu_1 \\
      \nu_2
    \end{pmatrix}
    \]
  - Difference in mass between neutrino mass eigenstates: \( m_1 \neq m_2 \)

http://www.ps.uci.edu/~superk
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Now for Amanda (Ice-cubed):
- 100’s of 8–9" pmts
- 1800m below ice surface at south pole
- PMTs detect Cherenkov light from muons traversing ice which were produced from TeV neutrinos rising up through earth

Sources?:
- Pulsars?
- AGN?
- GRB?

http://amanda.berkeley.edu
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- Amanda deployment pics:
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Cosmic Ray Summary:

- We’ve know about CRs for almost 100 years
- Still don’t know for sure of their origins
- First used to explore subatomic particles
- Significant constituent of solar system and galaxy
- Messengers from deep space
- Perhaps were significant in development of life on earth?
- Still hold many difficult but intriguing mysteries yet to be solved