A (very) Brief History of Cosmic Rays

Victor Hess, 1912:
- discovered cosmic rays in balloon flights,
  through discharge of Leyden jars

Pierre Auger, 1938:
- Research in Giant Air Showers showed energies of primary particles above $10^{16}$ eV -- truly unimaginary for the time!

• 1960’s: Cosmic rays with energies of $>10^{19}$ eV detected - how are they made??
• Greisen, Zatsepin, Kuzmin (GZK): there should be a limit at $\sim 5 \times 10^{19}$ eV
• Most particles are produced and decay a few kilometers above the ground
• Characteristic height for airshowers are 10-20 km
• Interaction height is energy dependent
• Most energetic particles are found relatively close to sea level
Sources of PeV to ZeV Neutrinos

Almost certain sources:
- Extragalactic cosmic rays
  - Produce the so-called GZK neutrinos
  - $10^{20}$ eV cosmic rays from $z \approx 1-10$ lead to EeV neutrinos through photopion interactions

Probable sources:
- Active galaxies:
  - strong evidence for acceleration of particles, EeV energies probable
- Gamma-ray bursters:
  - PeV to EeV predicted by many models

Exotic (but very interesting) sources:
- Topological defects
  - early universe relics (of many sorts)

Possibilities for radar detection of EAS

- Ionization produces a tenuous plasma, line densities of $10^{14}$ m$^{-1}$ for showers of $10^{20}$ eV at 10 km altitude
  - Similar to meteor electron line densities, but meteors at h~90km
- Plasma frequencies near the core of the shower may be ~10 MHz
  - Reflectivity at low frequencies may be very high—could account for early HF radar events
- High altitude air showers accessible to radar
  - Of order half of all high energy air showers do not produce particles at ground level, but occur as highly inclined showers at h=15-25 km
- Radar EAS detection could have high duty cycle
- Was original motivation for Lovell telescope
Radio Emission from Air Showers: History

- First discovery: Jelley et al. (1965), Jodrell Bank array at 44 MHz
- Confirmation from various groups in the 60ies
- Detections made from 2-520 MHz (e.g. Fegan 1970)
- Shower energies in the range $10^{17}$-$10^{19}$ eV

Advantages of Radio Airshowers

- Particle detectors only measure a small fraction of electrons or muons produced
- Height of cosmic ray interaction depends on energy
- Energy calibration is greatly improved by additional information (e.g., Cerenkov)
- Radio could
  - Observe 24hrs/day
  - See evolution of shower
  - Coherent emission reveals shape

Radio measurements are usually triggered by particle detectors
Radio-Emission from Air Showers: Current Activities

• Work ceased almost completely in the seventies (interference)
• Radio-experiment at CASA/MIA arrays (Rosner & Suprun 2001) failed because of man- and self-made interference
• An isolated group at Gauhati University (India) is observing regularly at 2-220 MHz
• Monte Carlo air shower radio code developed by Dova et al.
• RICE – Searching radio emission from neutrino induced showers in ice at the AMANDA site in Antarctica
• Search for radio emission on the moon (neutrinos; Alvarez-Muniz & Zas 2000; Gorham et al. 1999)

Radio Properties of Airshowers: Radio Amplitude – Empirical Results

\[ \varepsilon_{\nu} = K \frac{E_{\nu}}{10^{17} \text{eV}} \sin \alpha \cos \theta \exp \left( -\frac{R}{R_0(\nu, \theta)} \right) \text{ \( \mu \text{V m}^{-1} \text{MHz}^{-1} \)} \]

• Constant \( K \approx 15 \), \( R_0 \approx 110 \text{m} \), spectrum flat from \(~40-100 \text{ MHz}\)?
• \( S_{\nu} = \varepsilon_{\nu} \nu^2 / \text{MHz} \Rightarrow S_{\nu} = 26.5 \text{ MJy} (\varepsilon_{\nu} / 10 \text{ \( \mu \text{V m}^{-1} \text{MHz}^{-1} \)} )^2 \)
• \( R \) is distance from shower axis, relation corresponds to \(~1 \) degree half-angle emission cone
• Here \( \alpha \) is geomagnetic angle, \( \theta \) is zenith angle, but not measured past \(~50 \) deg.
• This relation is based on near field measurements: Fresnel zone for shower radio emission extends several tens of km, most data is from \( D \approx 5-7 \text{ km} \)!
Radio Properties of Airshowers: Energy Dependence of Amplitude

- Particle number: $N \sim E_p/\text{GeV}$
- Coherent or Incoherent radiation: $V \propto N$ or $V \propto N^{1/2}$, $S \propto V^2$
  \[ S \propto E_p \text{ or } E_p^2 \]
- Experimental results vary between the two cases.
- Note: shower height is energy dependent!

Radio Properties of Airshowers: Frequency Spectrum

- Simultaneous measurements at four frequencies between 44 and 408 MHz (Spencer 1969)
- Spectrum decreases as $V \propto v^{-1}$ or $S_v \propto v^{-2}$
- May continue down to 2 MHz (Allan et al. 1969).
- Noise level favors 40-50 MHz observations
Radio Properties of Airshowers: Spatial Extent

- The particles move as a flat (2-3 m thick) pancake around a central core through the atmosphere.
- The radio emission falls off steeply beyond a characteristic distance from the shower core ($R_0=50-500\text{m}$) ⇒ beaming

Radio Properties of Airshowers: Event Rates

- CR flux drops as $E_p^{-2}$
- $\sim 1$ particle m$^{-2}$ sterad$^{-1}$ year$^{-1}$ at $E_p \sim 10^{16}$ eV
- For a highly directional hundred meter dish ($10^{-4}$ sterad) this gives an event rate of only $\sim 1/yr$.
- Low-gain antennas have commonly been used
Radio Properties of Airshowers: Pulse Shapes

- The pulse shape measurements are usually bandwidth limited
- \( \delta t \sim 1 / \delta \nu \)
- At low frequencies \( \delta \nu \) usually was of order 1 MHz
  \( \Rightarrow \delta t \sim 1 \mu s \)
  \( \Rightarrow \) At 520 MHz a resolution of 70 ns was achieved

Radio Properties of Airshowers: Pulse Shapes

- Total shower duration is 30 \( \mu s \) (10 km/c)
- Doppler effect shortens pulse to 10 ns
- Pulses were typically unresolved with a bandwidth limited resolution of 1 \( \mu s \).
- Unconfirmed structure (doublets) on 70 ns scale
Radiation Mechanism: Coherent Synchrotron!?

- The characteristic energy where electrons disappear through strong ionization losses is 30-100 MeV, i.e. $\gamma \sim 60-200$.
- Geomagnetic field is 0.3 Gauss
- Electrons will "gyrate" along a small arc
- Electrons are in a thin layer of 2 meters thickness, i.e. less than a wavelength at 100 MHz
- Coherent emission can be produced (gives $N^2$ enhancement), beamed into propagation direction

AKA: "a form of Lorentz-boosted dipole radiation from geomagnetic charge separation"

Radiation Mechanism: Coherent Synchrotron!?

- Synchrotron power is given by the Poynting vector (charge & accel.)
- Acceleration is due to the Lorentz force
- N electrons act coherently as one particle of charge $N \cdot e$ and mass $N \cdot m$
- Power is increased by $N^2$ (amplitudes add coherently)

\[
P_q = \frac{2q^2 \gamma^2}{3c^3} \vec{r} = \frac{e}{\gamma mc} \vec{v} \times \vec{B}
\]

\[
\Rightarrow P_q = \frac{2q^2}{3c^3} \gamma^4 \frac{q^2 v_\perp^2 B^2}{\gamma^2 m^2 c^2}
\]

\[
\Rightarrow P_q = \frac{2q^4}{3c^5 m^2} \gamma^4 v_\perp^2 B^2
\]

\[
q = N \cdot e; m = N \cdot m_e
\]

\[
\Rightarrow P_q = N^2 P_e
\]
**Radiation Mechanism:**

Coherent Synchrotron!?

\[
B = 0.3G \quad ? = 60 \quad N_e = 10^6 E_{p,17} \\
A = p(10\ \text{km} \cdot 0.5\) \right)^2 \\
\nu_c \approx \frac{3e}{4p_e_c} \nu^2 B \approx 4.5\ \text{GHz} \\
S_\nu = N_e^2 p_e A^{-1} \left( \frac{?}{?_c} \right)^{1/3} \\
S_\nu(100\ \text{MHz}) \approx 40\text{MJy} \cdot E_{p,17}^2
\]

- Characteristic values for airshowers
- At the characteristic frequency coherence is not achieved due to finite thickness (decreasing spectrum)
- Predicted value matches fairly well observations.

**Neutrino-induced air showers**

- At \(10^{19}\) eV, horizontal neutrinos have 0.2% chance of producing a shower along a ~250 km track, 0.5% at \(10^{20}\) eV

- Could be distinguished from distant cosmic ray interactions by radio wavefront curvature: neutrinos interact all along their track with equal probability thus are statistically closer & deeper in atmosphere
  - Example of tau neutrino interactions: resulting tau lepton decay produces large swath of particles, out to 50km
  - Left: ground particle density from electron decay channel. Right: from pion decay channel
  - Results from studies for Auger air shower array, Bertou et al. 2001, astro-ph/0104452
Confirmation of Askaryan’s Effect: SLAC Lunacee 2 Experiment

“Charge asymmetry in showers leads to coherent radio Cherenkov emission”

- Use 3.6 tons of silica sand, brems photons to avoid any charge entering target $\Rightarrow$ no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!
- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Saltzberg et al, PRL, April 2001

Is it coherent Cherenkov?

- 100% linearly polarized pulses
- Plane of polarization aligned with plane of Poynting vector and cascade track
- No departures from coherence
  - field strength $\sim \gamma^2$ – shower energy
- Frequency dependence also as expected for CR: $E \sim \nu$
Goldstone Lunar Ultra-high energy Neutrino Experiment (GLUE) Radio Detection Approach

- RF pulse spectrum & shape

- Effective target volume: Antenna beam (~0.3 deg) times ~10 m moon surface layer
  $$\Rightarrow 100,000 \text{ cubic km!!}$$

- Limited primarily by lifetime: only a small portion of antenna time can typically be devoted to a single project

Lunar Regolith Interactions & RF Cherenkov radiation

- At ~100 EeV energies, neutrino interaction length in lunar material is ~60 km

- $$R_\text{moon} \sim 1740 \text{ km, so most detectable interactions are grazing rays, but detection not limited to just limb}$$

- Refraction of Cherenkov cone at regolith surface “fills in” the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon

- GLUE-type experiments have huge effective volume $$\Rightarrow$$ can set useful limits in short time

- Large VHF array may have lower energy threshold, also higher duty cycle if phasing allows multiple source tracking
FORTE: A space-based $10^{20}$ eV neutrino & cosmic ray detector?

FORTE: Fast On-orbit Recording of Transient Events satellite
- Pegasus launch in mid-1997
  - 800 km orbit, 3 year planned life
  - Testbed for non-proliferation & verification sensing
  - US Dept. of Energy funded, Los Alamos & Sandia construction & operation
  - Scientific program in lightning & related atmospheric discharges
- 30-300MHz range, dual 20 MHz bands, 16 1MHz trigger channels
  - ~3M triggers recorded to date
- FORTE can trigger on radio emission from Giant air showers $E \sim 100$ EeV
- Preliminary estimates: could be $\sim 50-100$ $10^{20}$ eV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL, LANL) planned this year

Scientific Goals

- Connects to “Origin of Cosmic Rays” & “Bursting Universe”
- Investigate extremely short-lived bursts
- Understand radio emission from air showers (polarization, spectrum, energy dependence, extent, evolution)
- Improve energy calibration of air shower arrays
- Study composition of UHECR
- Detect UHECR and solve GZK mystery
- Search for ultra-high energy neutrinos in the atmosphere, from the ground, on the moon
NRW Airshower Array
The Idea

- Measure cosmic rays from $10^{16}$ to $10^{20}$ eV
- Need 5000 sqm with station spacing of a few $10^{2-3}$ m
- Local coincidence
- Place stations on public buildings and schools
- Connect through internet
- Stations transportable, could be installed near LOFAR
- Money available for astroparticle physics

Considerations for a large ground array

- Intrinsis pulse widths from all processes are 10 ns or less
- High sampling bandwidth for triggered events, pulse shape may be critical discriminator
- Antenna BW may be limitation, but full BW should be sampled
- Low directionality, large beam
- High dynamic range (1-bit sampling is not enough)
- External trigger possible
- Short-term storage for burst data and retrospective beam forming
- For lunar pulse observations, dedispersion is an issue: daytime pulse smearing of several microsec for ~10 MHz of BW at ~100 MHz
- Low elevation angle beam response is desirable
- Very interesting events come at high zenith angles or from below (e.g., neutrinos)
Considerations (cont.)

- An array of at least ~100 km diameter required to be competitive with existing & planned ground arrays
  - ~3000 km² sr necessary, larger is better
  - Spacing of several hundred m to 1 km for thresholds of 1-10 EeV
  - Dual polarization & ns pulse timing will help with interference rejection
  - Can one “image” the shower and see its evolution?
  - An R&D program is necessary to develop solid criteria for recognizing these events if they are to be recognized without particle coincidence

Conclusions

- Time is ripe to renew efforts in air shower radio detection
  - The radio airshower connection is still not well understood
  - Potentially powerful & economic approach toward super-GZK astroparticle physics
  - New results in coherent radio pulses from cascades indicate that these effects can be very strong at high energies
  - RF technology - amplifiers, receivers, digital techniques—are greatly improved since 1970 ready for new applications
- Detection of EeV neutrinos will pave the way for a new astronomy
  - Air shower radio detection may be the dark horse in this race!
But remember ....

„... a single tractor in an adjacent field has been known to wreak havoc with reception of air shower pulses in an otherwise favourable site.“

(Allan 1971)