LOFAR & Air Showers

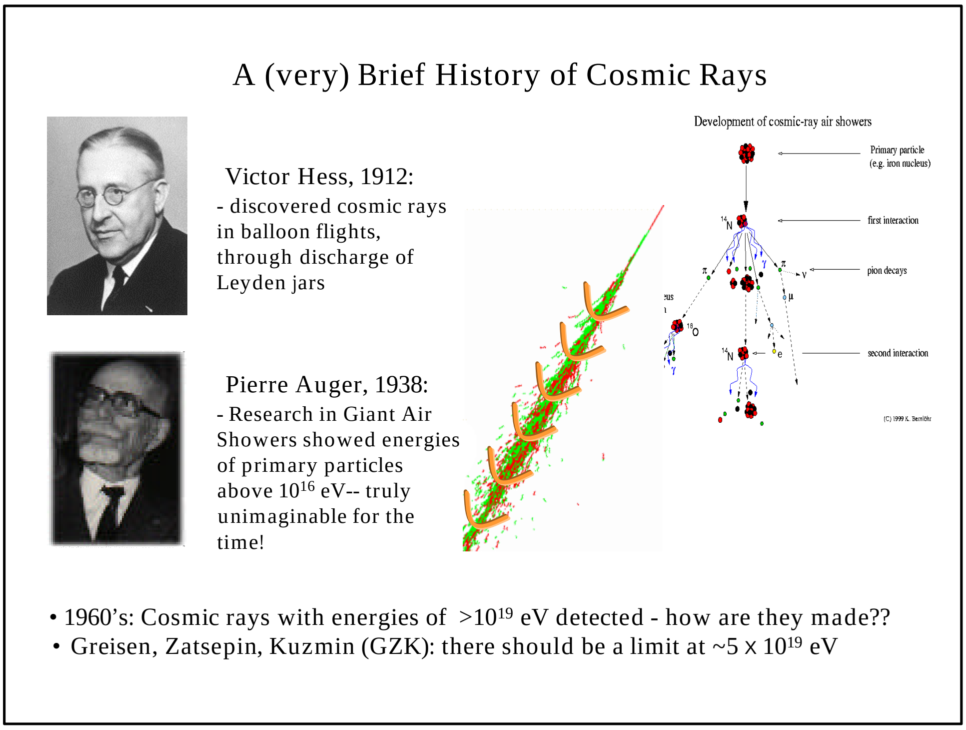
Heino Falcke

Max-Planck-Institut für Radioastronomie

&

Peter W. Gorham

JPL/NASA/Caltech



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 unimaginable for the time!

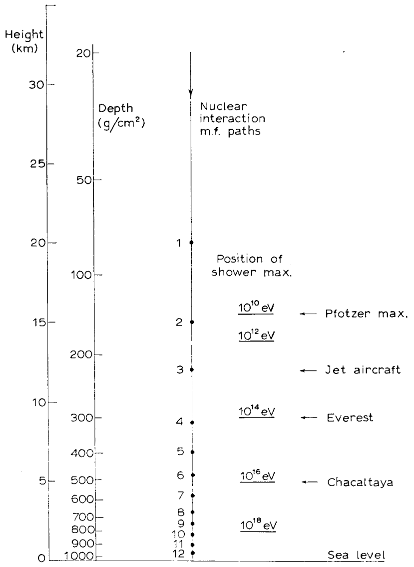
Development of cosmic-ray air showers

- 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 ~5×10^{19} eV

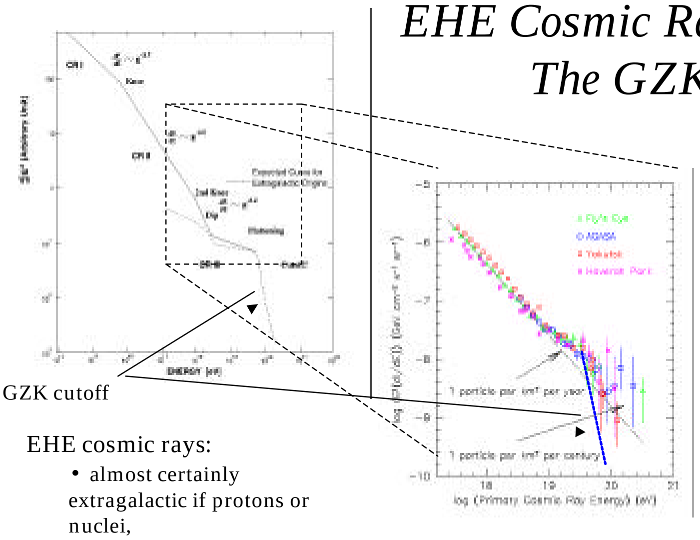
$$\frac{dN_{max}}{N_{max}} = \frac{dE_p}{E_p},$$

$$\frac{dx_{max}}{\lambda} = \frac{1}{\lambda}\frac{20}{2.718}\left[\log_{10}\frac{E_p}{10^{10}}\right]\frac{dE_p}{E_p}.$$

- •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



EHE Cosmic Rays & The GZK edge

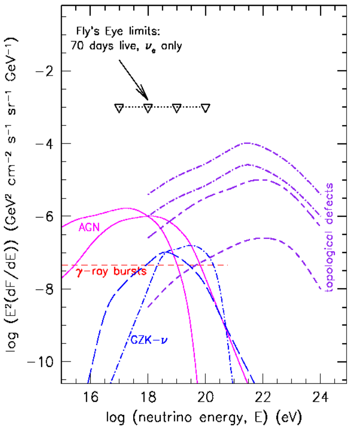


EHE cosmic rays:

- almost certainly extragalactic if protons or nuclei,
- MFP in 3K photon background is ~10Mpc--the very local universe!

- No GZK edge is yet seen
- Is there an enhancement where the cutoff should be….?

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~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:

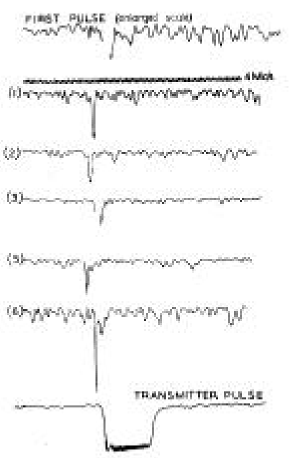
- Topological defects
  - early universe relics (of many sorts)

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

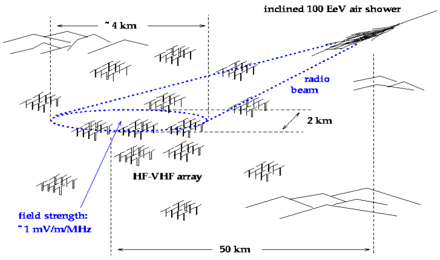
- First discovery: Jelley et al. (1965), Jodrell Bank array at 44 MHz
- Confirmation from various groups in the 60ies
- Detections made from 2-520 MHz (e.g. Fegan 1970)
- Shower energies in the range 10^{17}-10^{19}eV



Jelley et al. (1965)

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

$$\mathcal{E}_\nu = K \frac{E_p}{10^{17}\,\mathrm{eV}} \sin\alpha \cos\theta \exp\left(-\frac{R}{R_0(\nu,\theta)}\right) \quad \mu\mathrm{V}\ m^{-1}\ \mathrm{MHz}^{-1}$$

Allan (1971)

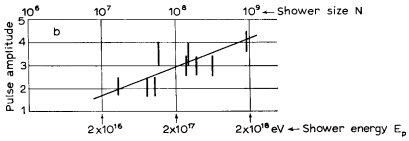
- Constant K~15, R_0~ 110m, spectrum flat from ~40-100 MHz?
- $S_\nu=\varepsilon_0 c\, \boldsymbol{e}_\nu^2/\mathrm{MHz} \Rightarrow S_\nu = 26.5\ \mathrm{MJy}\ (\boldsymbol{e}_\nu / 10\ \mu\mathrm{V\ m^{-1}\ MHz^{-1}})^2$
- R is distance from shower axis, relation corresponds to ~1 degree half-angle emission cone
- Here α is geomagnetic angle, θ 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~5-7 km!

Radio Properties of Airshowers: Energy Dependence of Amplitude

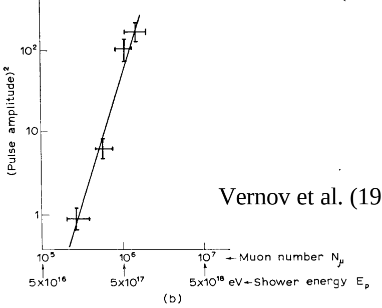
- Particle number: $N{\sim}E_p/\mathrm{GeV}$
- Coherent or Incoherent radiation: $V \propto N$ or $V \propto N^{1/2}$, $S_n \propto V^2$

$\Rightarrow S_\nu \propto E_p$ or E_p^2

- Experimental results vary between the two cases.
- Note: shower height is energy dependent!



Barker et al. (1967)

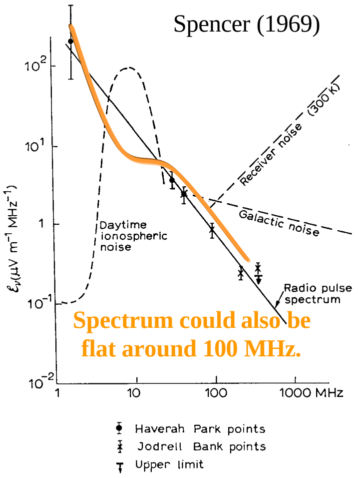


Vernov et al. (1986)

Radio Properties of Airshowers: Frequency Spectrum

- Simultaneous measurements at four frequencies between 44 and 408 MHz (Spencer 1969)
- Spectrum decreases as $V \propto \nu^{-1}$ or $S_\nu \propto \nu^{-2}$
- May continue down to 2 MHz (Allan et al. 1969).
- Noise level favors 40-50 MHz observations

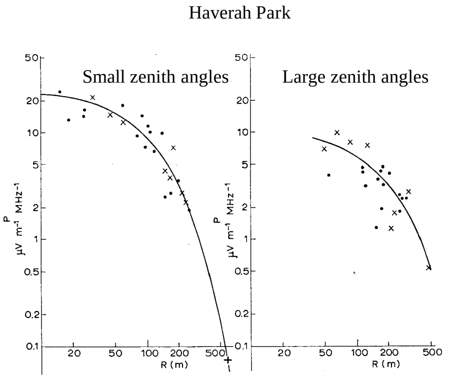
Spencer (1969)



Spectrum could also be flat around 100 MHz.

Radio Properties of Airshowers: Spatial Extent

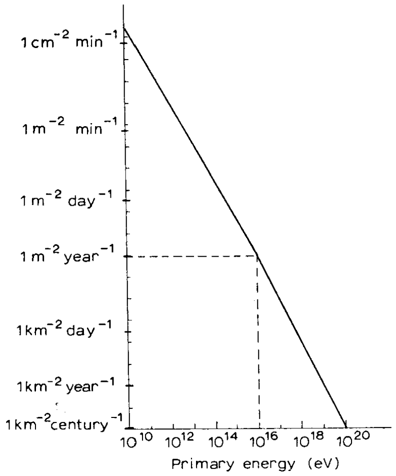
- The particles move as a flat (2-3 m thick) pancake around a central core through the atmosphere.
- The radio emission falls off steeply beyond a characteristic distance from the shower core (R_0=50-500m)⇒beaming



Amplitude normalized to $E_p=10^{17}$eV

Radio Properties of Airshowers: Event Rates

- CR flux drops as E_p^{-2}
- ~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 ~1/yr.
- Low-gain antennas have commonly been used

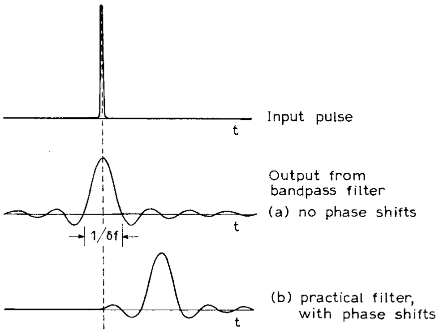


Radio Properties of Airshowers: Pulse Shapes

- The pulse shape measurements are usually bandwidth limited
- δ t ~ 1 / δ ν
- At low frequencies δ ν usually was of order 1 MHz

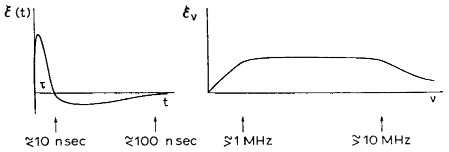
⇒δ t ~ 1 µs

⇒At 520 MHz a resolution of 70 ns was achieved



Radio Properties of Airshowers: Pulse Shapes

- Total shower duration is 30 µs (10 km/c)
- Doppler effect shortens pulse to 10 ns
- Pulses were typically unresolved with a bandwidth limited resolution of 1 µs.
- Unconfirmed structure (doublets) on 70 ns scale



Radiation Mechanism: Coherent Synchrotron!?

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

- The characteristic energy where electrons disappear through strong ionization losses is 30-100 MeV, i.e. γ~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

Radiation Mechanism: Coherent Synchrotron!?

$$P_q = \frac{2q^2\ddot{\vec{r}}^2}{3c^3} \qquad \ddot{\vec{r}} = \frac{e}{?mc}\vec{v}\times\vec{B}$$

$$\Rightarrow P_q = \frac{2q^2}{3c^3}?^4\frac{q^2v_\perp^2B^2}{?^2m^2c^2}$$

$$\Rightarrow P_q = \frac{2q^4}{3c^5m^2}?^2v_\perp^2B^2$$

$$q = N\cdot e;\, m = N\cdot m_e$$

$$\Rightarrow P_q = N^2P_e$$

- 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 · e and mass N · m

⇒ Power is increased by N^2 (amplitudes add coherently)

Radiation Mechanism: Coherent Synchrotron!?

$$B = 0.3G \quad ? = 60 \quad \mathrm{N_e} = 10^8 E_{p,17}$$

$$\mathrm{A} = \mathrm{p}(10\,\mathrm{km}\cdot 0.5°)^2$$

$$?_\mathrm{c} \sim \frac{3e}{4\mathrm{p}m_e c}?^2 B \sim 4.5\,\mathrm{GHz}$$

$$S_? = N_e^2 P_e A^{-1} ?^{-1} \left(\frac{?}{?_\mathrm{c}}\right)^{1/3}$$

$$S_?(100\,\mathrm{MHz}) \sim 40\mathrm{MJy}\cdot E_{p,17}^2$$

- 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

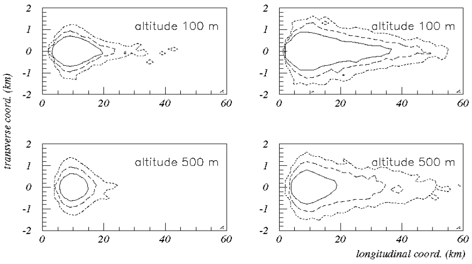


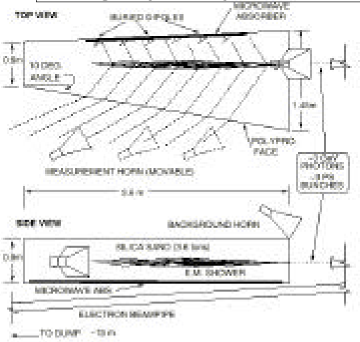
Figure 3. Ground spots of horizontal showers induced by a τ of 1 EeV. Lines are iso-density curves at the threshold of the tank local trigger (solid), at 0.3 (dashed) and at 0.1 (dotted). All of this data (even when below threshold) can be used if a global trigger could be generated from a set of local triggers. Left: τ decay into $e\nu_e\nu_\tau$; right: decay into $\pi\nu_\tau$

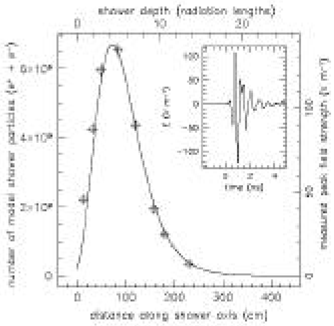
- Example of tau neutrino interactions: resulting tau lepton decay produces large swath of particles, out to 50km
- Left: ground particle density from electron decay channel. Right: from pion decay channel

- Results from studies for Auger air shower array, Bertou et al. 2001, astroph/0104452

Confirmation of Askaryan’s Effect: SLAC Lunacee 2 *Experiment*

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



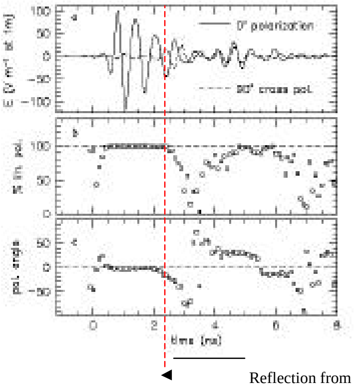


- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!

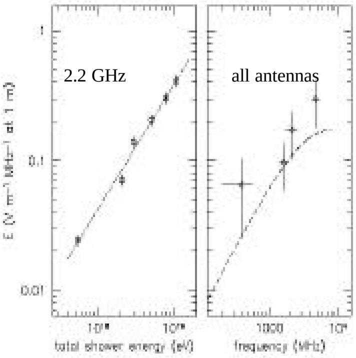
- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Saltzberg et al, PRL, April 2001

Is it coherent Cherenkov?

2.2 GHz data:



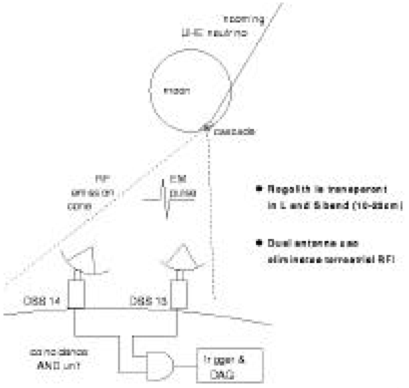
Reflection from side wall



- 100% linearly polarized pulses
- Plane of polarization aligned with plane of Poynting vector and cascade track

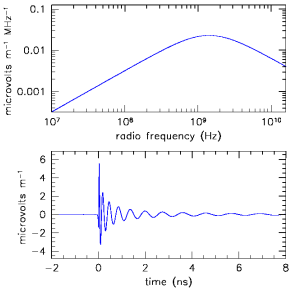
- No departures from coherence
  - field strength ~ Nγ ~ shower energy
- Frequency dependence also as expected for CR: E ~ ν dν

Goldstone Lunar Ultra-high energy Neutrino Experiment (GLUE) Radio Detection Approach



- Regolith is transparent in L and S band (10-20cm)
- Dual antenna also eliminates terrestrial RFI

- RF pulse spectrum & shape

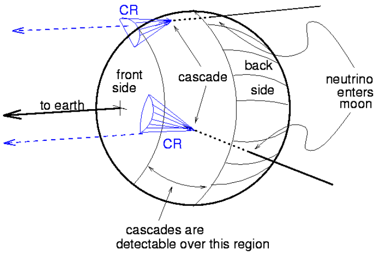


- Effective target volume: Antenna beam (~0.3 deg) times ~10 m moon surface layer

  ===> ~100,000 cubic km!!

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

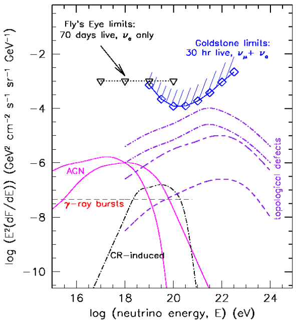
Lunar Regolith Interactions & RF Cherenkov radiation



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

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

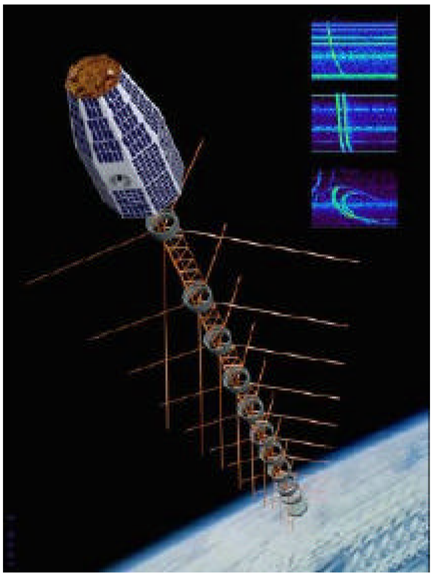
- Refraction of Cherenkov cone at regolith surface “fills in” the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon



- GLUE-type experiments have huge effective volume ➔ 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

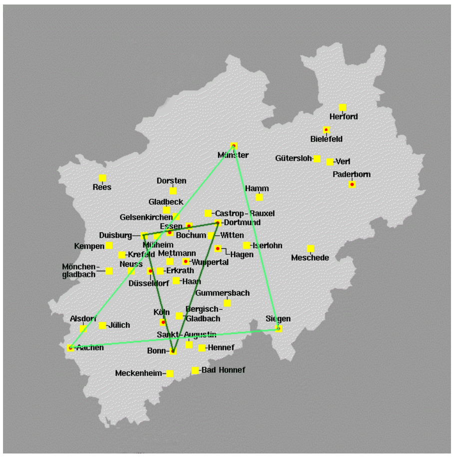
- FORTE can trigger on radio emission from Giant air showers E~100 EeV
- Preliminary estimates: could be ~50-100 10^{20} eV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL,LANL) planned this 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

- Intrinisic 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 km^2 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)