Lightnings

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X Astroteilchenschule,
Bärnfeld, 03.10.2013
Lightnings and Cosmic Rays

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Charge and Current of the Atmosphere

- Constant positively charged atmosphere and negatively charged ground
- Potential of ca. 300 kV, most dropping below 20 km
- Current of 1 kA (2 pA/m²)

Conductivity of atmosphere:
- $10^{-11}$ S m⁻¹ @ 35 km
- $10^{-14}$ S m⁻¹ @ sea-level
- $10^{-3}$ S m⁻¹ for ground
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Lightning in a nut-shell

- Inter-/intra-cloud discharges (IC) ca. 75%
- Cloud to Ground lightnings (CG)
- 90% of CG is negative

- Leader duration ca. 1 ms
- Overall lightning ca. 200 ms
- 20% single stroke, usually 3-5
- Charge 20 C, Energy $10^9$ to $10^{10}$ W
Positive Cloud-Ground Lightning

Lightning arcs from the top of a cloud to the horizon off the coast of the Bahamas.

- can be positive
- rare
- usually more powerful
- from farther up in the cloud (16 km)
Electrons in Air

25 MeV electron in air (1 atm)

25 MeV electron in air (1 atm) in a 300 kV/m electric field
Electrons in Air

Bethe Bloch energy-loss

25 MeV electron in air (1 atm) in a 300 kV/m electric field

\[ F(eE/cm) \]
\[ eE_c \]
\[ eE \]
\[ eE_{th} \]

\( F \) vs. kinetic energy (keV)

\( eE_c \) is the critical energy, \( eE \) is the energy loss, \( eE_{th} \) is the threshold energy.
Lightning initiation problem

- Decades of in situ electric field observations showed field-strength in cloud of $4 \times 10^5$ V/m ($n/n_0$ scaled)
- $x10$ too small for spark ($E_b = 2.6 \times 10^6$ V/m)

Relativistic Runaway Electron Avalanche:
- the electrons gain more energy than they loose by interaction in air
- $E_{RREA} = 2.84 \times 10^5$ V/m
- X-ray emission and positions in avalanche backpropagate may feedback the seed electrons
Movies from:
http://www.lightning.ece.ufl.edu/
Rocket ignited lightning

Rocket with trailing copper wire
Launch at 10kV / m on ground
Lightning probability of 60%

Rakov et al., 1998

- Natural channel
- Wire-trace channel
- Copper wire

- \( \sim 10^7 \text{ m/s} \)
- \( \sim 10^8 \text{ m/s} \)
- \( \sim 2 \times 10^2 \text{ m/s} \)
- \( \sim 10^5 \text{ m/s} \)
- \( \sim 300 \text{ m} \)
- 1-2 s

- Ascending rocket
- Upward positive leader
- Initial continuous current
- No-current interval
- Downward negative leader
- Upward return stroke

03.10.2013, J. Rautenberg Lightning and CR
Lightnings and Cosmic Rays
at LOPES and AUGER
3000 km² at 1400 m
1660 Surface Detectors
27 Fluorescence Telescopes
EAS over Wuppertal

10 EeV proton shower at 75 degree
S. Querchfeld; visualizations Univ. Chicago; shower S. Sciutto’s AIRES
Autonomous Particle Detector

Cherenkov light in water

Battery

3 – Photomultiplier

Electronic cover

Plastic tank filled with 12 tons of water

Communication-antenna

GPS antenna

Solar panel
Camera System

- 24+3 telescopes
- 12 m² mirror
- 30° x 30° field of view
- 440 PMT/camera
- 10 Mio pictures/s

UV Filter
opt. Filter (MUG-6)

440 PMTs camera
Hybrid measurement of extensive air shower

Stereo observation of an EAS

Los Morados

\[ \lg(E/eV) \approx 19.2 \]
\[ (\theta, \varphi) = (63.7, 148.4) \text{ deg} \]

Los Leones

\[ \lg(E/eV) \approx 19.3 \]
\[ (\theta, \varphi) = (63.7, 148.3) \text{ deg} \]

SD array:

\[ \lg(E/eV) \approx 19.1 \]
\[ (\theta, \varphi) = (63.3, 148.9) \text{ deg} \]
Energy spectrum to the highest energies

\[ E^3 J(E) \left[ \text{eV}^2 \text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1} \right] \]

\[ \log_{10}(E/\text{eV}) \]

\[ E [\text{eV}] \]

Auger 2013 preliminary
SD Trigger efficiency

SD-Trace: 40 MHz sampling

T1 (Single Station Level) → T2 (Single Station Level) → T3 (CDAS level)

13 bins
> 0.2 \text{ \text{VEM}}  \quad \text{2 Hz} \quad \text{ToT-T1}  \quad 13 bins
> 0.2 \text{ \text{VEM}}  \quad \text{2 Hz} \quad \text{ToT-T2}  \quad \text{ToT2C_1 & 3C_2}

1 bin
> 1.75 \text{ \text{VEM}}  \quad \text{100 Hz} \quad \text{TH-T1}  \quad 1 \text{ bin}
> 3.2 \text{ \text{VEM}}  \quad \text{20 Hz} \quad \text{TH-T2}  \quad 2C_1 & 3C_2 & 4C_4

LsId 276 - Claire

3ToT Efficiency

\[
\text{Signal [VEM]}
\]

\[
\text{log}_{10}(E/\text{eV})
\]

PMT 1, PMT 2, PMT 3

p infill array, Fe infill array

p regular array, Fe regular array

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SD-Scaler Measurements

- JINST 6 P01003 (2011)
- Count 12 ns bins with signal above 3 FADC counts (dE/dx \sim 15\text{MeV}) and upper bound of 20 FADC counts (\sim 100\text{MeV}) to remove muon background for GRBs searches
- Average \sim 2 \text{kHz}
- Good correlation with neutron monitors
- “Space weather”
Latest scaler data

![Graph showing scaler data trends over time.](image)

Should you use these data for any publication, acknowledgement to the Pierre Auger Observatory should be given and JINST 6 P01003 (2011) should be cited. You can also download an [ascii file] with all the dataset.
SD-Scaler Measurements

SD-Trace of a lightning event
Scalers count many “particles”
Analysis of Traces give better lightning-indicator
SD-Scaler Measurements

Xavier Bertou
http://www.youtube.com/watch?v=E0h36hPpeJE
SD-Scaler Measurements

SD-Trace of a lightning event
Scalers count many “particles”
Analysis of Traces give better lightning-indicator

Preliminary result:
No correlation with Auger-Events
due to high energy-threshold
log(E/eV)>18.5

Xavier Bertou
Lightning Detectors

- 60 – 66 MHz observation
- 25 MHz sampling
- Log detector


Lightning Mapping Array @ Auger


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Lightning and CR
Radio-Detection of Extensive Air Showers
Renaissance of Radio Detection: Theory

- Early measurements in the 70ties
- Full MC predicting few ns pulses with rather smooth falling frequency dependence and energy scaling
- Geomagnetic effect: $v \times B$
- Coherent emissions from billions of Elektrons
- Emission is focused in beam direction
Renaissance of Radio Detection: Theory

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Data from Prah (1971) and Spencer (1969)
Renewal of Radio Detection: Experiment

For R&D ideal environment:
- take a running experiment (KASCADE-Grande)
- add new hardware (from new experiment, LOFAR)
- have a look, how EAS look like (Nature 435, 2005)

- externally triggered
- understand radio-emission
  of extended air shower

energy-range from KASCADE-Grande
balance shower-rate and signal-height
LOPES: Interferometric Reconstruction

- Cross-correlated beam:

\[ cc[t] = \sqrt{\frac{1}{NPairs} \sum_{i=1}^{N-1} \sum_{j>i} s_i[t] s_j[t]} \]

- SNR scales with # antenna
- Pulse-height scales with energy

A. Horneffer et al. ICRC 2007

\[
\log(\text{Ratio Pulse Height})
\]

\[
\log(\text{Primary Energy/GeV})
\]

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Thunderstorm effect on CR's radio signal

In presence of thunderstorm radio signal can be enhanced by x10

Buitink et al. (LOPES Collaboration)

Apel et al. Advances in Space Research 48 (2011)
LOPES E-Fiels mill as Lightning detector

- Strong jumps of kV/m within 1 sec (sampling rate)
- Thunderstorm DAQ-mode reading longer traces

Apel et al. Advances in Space Research 48 (2011)
LOPES Lightning CR correlation with KASCADE

- Analysis of thunderstorm data for correlation
- Signal from relativistic runaway electron avalanche (RREA)?

No significant correlation found

Radio-Detection of Extensive Air Showers at Energies $E > 10^{18}$ eV
Radio EAS detection @ Auger

- 160 radio detector stations on 20 km$^2$
- Phase II deployed May 2013
AERA Station

- LPD Antenna 30-80 MHz
- GPS Antenna
- Solar panel
- Optical link (later wireless)

Electronic box:
- digital electronic
  (4x 12bit 200MHz ADCs)
- analog electronic
- batteries
Radio EAS detection @ Auger

- Example event for AERA I
- Well described by simulations
AERA E-field thunderstorm detection

- E-Field mill (Campbell Scientific CS110)
- No spatial resolution
- 1 sec sampling
- 2 stations at Auger
AERA E-field thunderstorm detection

- According to S. Nehls for Lopes
- Requirement:
  - E-Field over Threshold (500 V/m)
  - Jump in data larger then $|\Delta E_{-\text{field}}| > 2 \cdot \text{RMS}_{1\text{ min}}$
    - $> E_{\text{jump}} = 300 \text{ V/m}$
  - Change in slope larger then $40^\circ$
  - Sudden discharge due to lightning $(|\Delta E_{-\text{field}}| > 15 \cdot \text{RMS}_{1\text{ min}})$
- 15 minutes around found event are marked as thunderstorm
AERA E-field thunderstorm detection

- Available in Auger Monitoring
- Already at 25 km differences in detection on ground
Lightning detection for AERA

Boltek StormTracker:
- Sensitive in kHz-region
- Semiprofessional system
- Lightning detection up to 500 km
- Roughly estimation of direction via fraction of N/S and E/W polarization
- Three systems installed in November 2012 in Argentina
- Time accuracy of PC

Uncertainty of order 10 ms not enough for triggering other detectors
Lightning detection for AERA

CheckUp System (www.checkup-technik.de)
- 13 Boltek StormTracker with GPS-module in Germany
- Time of Arrival - Reconstruction
- ca. 100 m spatial resolution
- Webinterface delivers Google Earth data
Lightning detection for AERA

- Lightning data in Auger Monitoring available
- Clear signal e.g. for 9th of March 1:36 am elve
GPS-Extension for Boltek StormTracker

- ublox LEA-6T module
- Read out via USB
- Time Mark External Input from StormTracker Trigger
- Systematic ~ 20 ns
- Resolution ~ 10 ns
Lightning measuring with AERA

- LMA used 60-66 MHz, AERA uses 30-80 MHz
- Lightning measurements with 180 MHz sampling
- Modification of standard analysis for multiple pulses
- Need full buffer (7 sec) read-out
EFM triggered AERA Data


Angular Distribution

Lightning moving over the Array
Lightning correlation with CR

Lightning measurements in Auger with:
- Surface Detector,
- E-Field mill,
- Boltek StormTracker,
- Lightning Mapping Array,
- CR Radio Detector

Correlation difficult because needs
- Precise Lightning detection / measurement
- High energy CR (statistics)
- Radio-measurement promising, might do both, but needs verification