Radio detection of cosmic rays and the SKA

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Highest energy cosmic rays

- studied for 100 years
- origin not yet understood
- need high quality data
  - energy
  - mass!
- need large experiments
  - highest energy particles very rare

diagram by R. Engel
Extensive air showers and their detection

- Cosmic ray interacts with nucleus in atmosphere
- Cascade of secondary particles evolves
  - Particle detectors register particles at ground
  - Optical telescopes measure energy deposit via $N_2$ fluorescence
  - Radio detectors measure short (<100 ns) coherent radio pulses from time-varying currents
The Pierre Auger Observatory

- situated in Argentina
- covers 3000 km²
- 1600 particle detectors
  - “statistics”
- 24 optical fluorescence telescopes
  - “quality” (mass!)
- radio detectors deliver complementary information
CR radio pioneer – the LOPES experiment

- digital radio interferometer, frequency band 40-80 MHz
- 30 antennas on a 200 x 200 m area, 0.04 km²
- based on LOFAR prototype hardware
- integrated with KASCADE-Grande experiment
- has pioneered the technique
Interferometric reconstruction with LOPES

Sky map of a cosmic ray radio flash
H. Falcke et al. (LOPES Coll.), Nature 2005

~50 ns! unknown direction!

F.G. Schröder et al. (LOPES Coll.), ECRS2012
Individual event measured with LOPES

W.D. Apel et al. (LOPES Coll.), Astrop. Physics
On the way to high energies – AERA

for comparison: size of LOPES

- scale to higher energies
  - fully autonomous detector stations
  - antenna spacing 150-375 metres
  - currently 6 km² area

24 stations since early 2011
124 stations since May 2013

LOPES
AERA

Equivalent c.m. energy $\sqrt{s_{\text{pp}}}$ (GeV)

- $10^3$
- $10^4$
- $10^5$
- $10^6$

- Tevatron (p-p)
- 7 TeV 14 TeV LHC (p-p)
- HiRes-MIA
- HiRes I
- HiRes II
- Auger ICRC 2013
- TA 2011 (prelim.)

24 stations since early 2011
124 stations since May 2013

0 1 km 2 km 3 km 4 km

Currently 6 km² area
On the way to high energies - AERA

German SKA Science Meeting, 02/2014, Bielefeld
Individual event measured with AERA

CoREAS, QGSJET II.03 + URQMD
- proton simulation
  \( \langle X_{\text{max}} \rangle = 773 \pm 70 \text{ g/cm}^2 \)
- iron simulation
  \( \langle X_{\text{max}} \rangle = 677 \pm 18 \text{ g/cm}^2 \)
- measured data

- this is as good as it gets with AERA due to sparse antenna spacing

Pierre Auger Collaboration, ICRC2013, id #899
Detailed studies – LOFAR dense core

- O(800) antennas in 400 m diameter circle, \( \sim 0.1 \text{ km}^2 \)
  - either 30 – 80 MHz or 120 – 240 MHz
- small particle detector array (trigger & event information)
- allows us extremely detailed studies of individual cosmic rays
Individual events measured with LOFAR

- extreme level of detail
- but area of only ~0.1 km² limits reach in energy

S. Buitink for the LOFAR Collaboration, ICRC2013, id #579
Global fit of particle and radio LDF with LOFAR

Preliminary

$\chi^2 / \text{ndf} = 1.3$

$X_{\text{max}} = 637 \pm 20 \text{ g/cm}^2$

279 antennas

very competitive cosmic ray mass determination via depth of shower max

S. Buitink for the LOFAR Collaboration, ICRC2013, id #579
The SKA could play a very significant role here

- observing frequencies 50 – 350 MHz (now typically 30-80 MHz)
- bandwidth of 250 – 300 MHz (now typically 50 MHz)
- dense core of ~7 km$^2$

„detail of LOFAR on the scale of AERA“
- detailed mass-composition studies in range $10^{17}$ eV to $>10^{19}$ eV
Technical requirements

- read out ~50 µs original **raw data** of **individual antennas** upon trigger
- can run in piggy-back mode to normal observations
- has successfully been implemented in LOFAR

[Diagram of signal flow from radio antenna, through A/D conversion, trigger, storage, to LOFAR]

German SKA Science Meeting, 02/2014, Bielefeld

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Conclusions

- high-energy cosmic rays are a major research interest with large active collaborations (Auger has >500 authors)
- radio detection of cosmic rays has matured in the past few years and can deliver very competitive results
- the SKA could do cosmic ray research in the region of transition from galactic to extra-galactic cosmic rays
- this would require buffering (~few hundred ms) and readout of antenna raw data upon trigger by a small particle detector array
  - how much effort would that be? cf. transient studies …
Hillas Diagram

\[ E_{\text{max}} \sim \beta^2 \cdot z \cdot B \cdot L \]

- Gamma Ray Bursts?
- Neutronensterne
- \( \beta_s = 1 \)
- \( \beta_s = 1/300 \)
- Weiße Zwerge
- Aktive Galaktische Kerne?
- Interplanetarer Raum
- Supernova-Reste
- Galakt. \{ Scheibe Halo \}
- Jets aus Radio-Galaxien
- Galaktische Cluster
- Intergalaktische Materie
- LHC
- \( 10^{12} \) to \( 10^{-6} \) Gauss
- \( 1 \) to \( 10^6 \) km

\( L \) in Erdbahnradius, \( 1 \) pc, \( 1 \) kpc, \( 1 \) Mpc
Indications for sources

- indications for correlation with active galactic nuclei

- significance?
- light or heavy nuclei?

J. Abraham et al. (Auger Collaboration), Science 318 (2007) 938-943
Mass composition of UHECR

Composition seems to become heavier again at highest energies.
Radio emission physics

- primary effect: geomagnetic field induces *time-varying* transverse currents
  Kahn & Lerche (1967)

- secondary effect: *time-varying* net charge excess (Askaryan effect)

Askaryan (1962,1965)

"\( \mathbf{v} \times \mathbf{B} \)"

Diagrams by H. Schoorlemmer & K.D. de Vries

\[ \text{Radial} \]
Complexity of radio lateral distribution

vertical iron shower at LOPES frequencies simulated with CoREAS

TH et al., ARENA2012
Complexity of signal polarization

- complex time evolution of electric field vector
- superposition of geomagnetic and charge excess emission

CoREAS simulations, TH et al., see id 548
Lateral distribution as probe for composition

- simulations for proton and iron primaries show systematic differences

vertical proton shower at LOPES frequencies simulated with CoREAS

vertical iron shower at LOPES frequencies simulated with CoREAS

TH et al., ARENA2012
Large area needs large antenna spacings

- radio detection works well, but illuminated area is usually limited
  - investigate inclined showers
  - investigate lower frequencies
  - investigate hybrid analysis with single radio antenna
    - $X_{\text{max}}$ from pulse shape, spectral index?
    - $X_{\text{max}}$ from wavefront timing?

30° zenith angle

50° zenith angle

75° zenith angle

TH et al., this conference, id #548
LOPES has made quantitative analyses

- linear correlation with 20-25% combined LOPES-KASCADE-Grande energy resolution
  - radio probably better, limited by KASCADE-Grande energy uncertainty of ~20%
  - simulations: ~8% intrinsic

N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439

- also works with interferometric analysis, yielding again ~20% uncertainty

F.G. Schröder et al. (LOPES Coll.), ARENA2012
Xmax reconstruction with LOPES

- with simulations, radio LDF slope can be related to Xmax
- using parameterisations derived with CoREAS simulations, Xmax is estimated for each individual LOPES event (method $\sigma_{X_{\text{max}}} \sim 50 \text{ g/cm}^2$)


N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439