High energy cosmic particles

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also here in Stockholm: Justin Bray, Olaf Scholten
Cosmic ray all-particle spectrum

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

Scaled flux $E^{2.5} J(E)$ ($m^2 s^{-1} Sr^{-1} eV^{1.5}$)

two ECPs under consideration
Cosmic ray all-particle spectrum

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

Scaled flux $F(E)$ (m$^2$ s$^{-1}$ Sr$^{-1}$ eV$^{1.5}$)

atmospheric showers
accurate mass measurements
transition galactic - extragalactic?

two ECPs under consideration
Cosmic ray all-particle spectrum

atmospheric showers
accurate mass measurements
transition galactic - extragalactic?

lunar showers
nature of the cut-off
sources of ultra-high energy CRs

two ECPs under consideration
Atmospheric showers
Measure mass composition at $10^{17} - 10^{18}$ eV
to disentangle Galactic and extragalactic component

$E_{\text{max}} \sim 2 \beta c Z e B r$

transition to heavier composition = maximum source energy reached

established technique:
Fluorescence: $\sim 20$ g/cm$^2$, 15% duty cycle

radio method:
LOFAR in 2014: $< 20$ g/cm$^2$, 100% duty cycle
What drives the radio emission?

- **Earth magnetic field**
  electrons/positrons deflected
  \( E \sim d n_{ch}/dt \)

- **Charge excess**
  negative charge due to electron knockouts
  \( E \sim d(n_e-n_p)/dt \)

- **Non-unity index of refraction**
  Cherenkov-like effects
  ring structure possible

Coherent at 100 MHz (higher at Cherenkov angle!)
wavelength > shower front size
\( P \sim n^2 \)
LORA LOFAR Radboud Array scintillator detectors

trigger: 16 of 20 detectors

buffer
2 ms read-out

Low Band Antennas (LBA) 30 - 80 MHz

Superterp:
* diameter ~ 300 m
* 20 LORA detectors
* 6 LBA stations (= 6 x 48 antennas)
* more LBA stations around superterp

offline analysis
P. Schellart et al., A&A 560, 98 (2013)
Reconstruction of Xmax
- based on fitting 2D radio profile \( (S.B \text{ et al., PRD 90 082003 (2014)}. \)

**background:** CORSIKA / CoREAS

**circles:** data

**fit:** 2D radio + 1D particle

for each shower a **dedicated MC set** is produced:

50 p + 25 Fe

**Xmax reco:** use quality-of-fit

**energy reco:** from particles

resolution \( \sim 20 \text{ g/cm}^2 \)
SKA: ultrahigh precision measurements

Science:
- **origin of CRs**
  mass composition in transition region G/XG
- **hadronic physics at super-LHC energies**
  shower tomography
- **thunderstorm physics**
SKA: ultrahigh precision measurements

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Air showers in thunderstorms

- Regular: geomagnetic field induces traverse current (vxB direction)

- Strong E-field (E ~ cB): current direction changes

- Air showers in thunderstorms: different polarisation & different intensity pattern

- Allows remote sensing of thunderstorm fields!

- Also: 4D lightning mapping lightning triggering by air showers

Schellart et al. PRL 114, 165001 (2105)
Engineering change: buffering

- Cosmic Ray mode should run in the background continuously.

- Buffering of all individual antennas: raw data at least 8 bit, pref. 12 bit.
  Buffer depth 10 ms (trigger latency).
  Total 1.3 TB for 60k antennas.

- Data rate:
  50 µs per trigger
  ~1 trigger/min.
  Read out in bursts of 2.2 GB/s over 3s after trigger.
Engineering change: triggering

- Flat scintillator particle detectors for triggering
- Efficient at $10^{16}$ eV: spacing 50-100 m
- Baseline design: 180 former KASCADE detectors (3.6 m$^2$)
- **RFI/EMI mitigation:**
  - full shielding + possibility of burying underground
  - comm. over optical fibre
  - extensive testing planned at MWA, LOFAR sites

*input from other SWGs appreciated!*
raw time-series data provide powerful diagnostic tool:
- in-situ antenna response model calibration
- bad connections, switched cables, ns timing offsets, etc.
System diagnostics

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- in-situ antenna response model calibration
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Figure 8. Polarization footprint of a single air shower, as recorded with the LOFAR low-band antennas, projected onto the shower plane. Each arrow represents the electric field measured by one antenna. The direction of the arrow is defined by the polarization angle \( \hat{e} \times \hat{B} \) axis and its length is proportional to the degree of polarization \( p \). The shower axis is located at the origin (indicated by the black dot). The median uncertainty on the angle of polarization is 4 and the value for each antenna is indicated by the grey arrows in the background. Except for a few antennas in the lower left station they are mostly small, indicating that the pattern is not the result of a random fluctuation.
Ultra-High energy CRs

• What are the most energetic sources? (AGN, GRB, …?)

• cut-off: GZK effect or source power?

• search for top-down particles: decaying cosmic strings supermassive particles
sources above 57 EeV?

Pierre Auger, southern hemisphere
isotropy rejected

Telescope array, northern hemisphere
hotspot 3.4 sigma

More statistics needed at highest energies

Super-Auger arrays not funded yet, space missions uncertain

SKA could be first observatory to reach sufficient aperture!
$10^{20} - 10^{22} \text{ eV: Moon} = 10^7 \text{ km}^2 \text{ detector area}$

- Goldstone
- VLA
- Kalyazin
- LOFAR
- Westerbork
- radio flash ns scale!
- ATCA
- Parkes
- CR/neutrino
- LaLUNA
- Lovell
- GLUE
- Goldstone 1999-2004
- RESUN
- VLA 2008-09
- NuMoon
- Westerbork 2008
- LOFAR UHEP
- Lovell 2010
- LUNASKA
- ATCA 2006-2012
- RamHand
- C.W. James, 34th ICRC, The Hague, NL
Askaryan effect

neutrino/CR

hadronic cascade

shower front ~10 cm

e\text{--} and \gamma\text{--} scattering:
negative charge excess

coherent Cherenkov emission
< 3 GHz
Escape from the Moon

- Askaryan radiation from cascade charge excess
- Cherenkov angle = angle of total internal reflection (for cascade parallel to surface)
- Up-going showers: only at rim of Moon
- Surface roughness helps!
• large spread around Cherenkov angle

• also radiation for down-going cascades:
  whole visible Moon surface = target ($\sim 10^7$ km$^2$)
Radio propagation simulation
Radio propagation simulation
low frequencies can escape!
Observation strategy

The lunar Askaryan technique: a technical roadmap

Figure 1: Beamforming strategy for lunar Askaryan observations with the SKA, with the beam from each station centred on the Moon, and all core stations synthesised into multiple array beams directed at different points on the Moon. These points are selected around the limb of the Moon, from which a signal is most likely to be detected. The size of the station beam shown is for the FWHM at the top of the 100–350 MHz band, and the array beams are for the geometric centre of this range.

SKA1-LOW will consist of 131,072 log-periodic dipole antennas, grouped into ⇐450 stations of 35 m diameter, each with ⇐300 densely-packed antennas. The majority of the stations will be grouped within 1 km, forming a dense core to the array, with the remainder spread out over baselines of up to ⇐80 km. The total collecting area will be less than 1 km²; this milestone will be reached with phase 2.

3. Beamforming

Because the antennas of SKA1-LOW are immobile, pointing of the telescope will be done electronically, with signals from all antennas in a station being summed with appropriate delay offsets to form a station beam pointed at an arbitrary point on the sky. The full width half maximum (FWHM) size of a station beam has a minimum value of 1.4 at the top of the band, which is sufficient to view the entire Moon, as shown in figure 1.

For high-time-resolution observations such as these, SKA1-LOW will have an array-level beamformer, combining multiple station beams in a similar fashion to form an array beam. By summing station beams with different delay offsets, this beamformer will be able to form multiple array beams simultaneously, with a planned capacity of 16 dual-polarisation beams with the full bandwidth. The size and sensitivity of these array beams depends on the set of stations used to form them. If only stations in the dense core of the array are used, the beams are large enough for them to be tiled completely around the limb of the Moon (see figure 1), achieving an efficiency factor of ⇐50% of the particle aperture for full lunar coverage, which is incorporated into the simulations.

Figure 4: The signal path of the HECP lunar observation mode. Operations which were a part of SKA-low Phase 1 baseline design are shown in red; those implemented as part of recent ECPs in blue; and those which will be performed by specialised lunar pulse detection hardware (the triggering unit, to be built by the HECP-lunar group) are in green. Interfaces between these systems are highlighted by orange arrows. For more detail on the triggering unit, see Fig. 6.

Pulse in real time and send a trigger signal to the SKA hardware. The operations required of this component, and the envisioned hardware, are described in more detail in Sec. 5.

Upon a trigger being generated, buffered station beam data from both core and remote stations will be sent to storage for offline analysis in the same manner as described for the transients search mode ECP 150004. The rate of triggering will be higher, yet the amount of data returned much lower, and we provide details in Sec. 4.3.

This mode has been simulated using the standard simulations package (James & Protheroe, 2009) as in the science chapter Bray et al. (2014). Updated estimates of the sensitivity to neutrinos and cosmic rays are given in Sec. 2, while the necessary engineering changes to implement it are the subject of Secs. 4 and 5.

4 Required engineering changes

Below are detailed the specific engineering modifications required to implement the lunar pulse detection mode described in Sec. 3 on SKA-low Phase 1.

4.1 Access to pulsar beamformer tied beams

The SKA-low Phase 1 pulsar beamformer will produce 16 dual-polarisation tied beams at 250 MHz bandwidth. In standard pulsar timing mode, this data will be directed to a specialised pulsar backend for real-time processing. For the HECP-lunar mode, these beams will be triggered and readout to storage.

The trigger rate is 0.1-1 Hz, and read-out time is 10 µs/station.
Figure 5: The 'Bedlam Board' (Bray, Ekers & Roberts, 2013): a purpose-built dedispersion and triggering unit built for LUNASKA observations at the Parkes radio telescope. It is capable of digitising and de-dispersing eight $512$ MHz data streams, and performing a real-time search anticoincidence search for nanosecond pulses with $0.5$ ns timing precision.

Figure 6: Overview of the triggering unit to be provided by the HECP group to enable these observations. $N_{\text{beam}} = 32$ timing beams (counting each polarisation separately) from the SKA1-low beamformer are each searched for a possible signal with a search module as shown in Fig. 10. If a pulse is detected, and passes anticoincidence logic to exclude RFI, a trigger signal is generated and passed to the SKA system, requesting the storage of a $\llap{\sim}10\,\mu s$ chunk of buffered station data. A local buffer of beamformed data is also stored, as a check on the beamformer output and the function of the triggering unit. For the interaction of this unit with other components, see Fig. 4.

**Observation strategy**

- **PFF inversion**
  subbands $\rightarrow$ timeseries data

- **ionospheric dedispersion**

- **trigger logic**
  select localised pulses

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**Triggering unit**

*(to be provided by HECP group)*
Sensitivity to UHECR

- Phase 2:
  - $A_{\text{eff}} > 100,000 \text{ km}^2 \text{ sr}$ at $10^{20} \text{ eV}$
  - 50 UHE CR yr$^{-1}$ at $E > 56 \text{ EeV}$

<table>
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<tr>
<th>Phase</th>
<th>$A_{\text{eff}}/T_{\text{sys}}$ (m$^2$ K$^{-1}$)</th>
<th>$f_{\text{min}}$ (MHz)</th>
<th>$f_{\text{max}}$ (MHz)</th>
<th>Beam Coverage</th>
<th>$\sigma_{\text{thresh}}$</th>
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<tr>
<td>Phase 1</td>
<td>250</td>
<td>100</td>
<td>350</td>
<td>$\sim 50%$</td>
<td>7</td>
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</tbody>
</table>

C.W. James, 34th ICRC, The Hague, NL
Angular resolution

- Instantaneous sensitivity of the SKA-Moon detector

- Signal strength: $10\sigma$ (±1)
- Polarisation: $5^\circ$ (as $\arcsin(1\sigma/10\sigma)$)
- Inner 10km: 0.5’ at 100 MHz

- ‘Resolution’: ~5° region
- Any explicit reconstruction should do better!

Sources(?) in range: Cen A, Sgr A*, M87, …
Limits on UHE neutrinos with 1000 hr

● Strong constraints on remaining top-down models
summary

• **Atmospheric showers**
  - SKA aperture 10x LOFAR (+ increased freq. bandwidth)
  - Science: CR origin, super-LHC hadronic interactions, thunderstorm physics
  - Observations run continuously in background (100% commensal), raw data diagnostics could help all other observations.
  - RFI/EMI: not a problem at LOFAR; extensive testing foreseen; *input from other SWGs appreciated!*

• **Lunar showers**
  - very challenging, but potentially huge breakthrough
  - identification of ultra-high-energy sources
  - proof-of-principle SKA-phase 1; astrophysics in phase 2
  - needed ~1000 hrs observation, *commensality: CD/EoR* *(Vedantham et al 2015), pulsar search, FRBs, SETI, … (?)*