High Energy Cosmic Particles

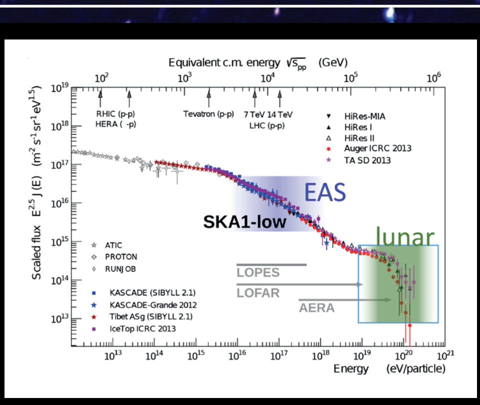
Focus Group

Somewhere in the Universe, particles are being accelerated to energies up to ten million times higher than those achieved by particle accelerators like the Large Hadron Collider. These particles, known as cosmic rays, are the most energetic in nature, subject to laws of physics that are otherwise beyond our reach. When they collide with mundane matter, such as the Earth's atmosphere or the surface of the Moon, they produce cascades of secondary particles that generate a burst of radio waves lasting only a few billionths of a second. The High Energy Cosmic Particles Focus Group will use the SKA to study these rare particles, to understand the physics of their interactions and the mystery of their origin.

The cosmic-ray spectrum

Cosmic rays are composed of the same stuff as interstellar gas: mostly protons and atomic nuclei. Their spectrum (see figure) extends over a huge energy range. We think that cosmic rays with lower energies, up to perhaps 10^{17} eV, are being produced by something in our own Galaxy: the remnants of supernovae, or the supermassive black hole at the Galactic Centre. At higher energies only extragalactic objects, such as active galactic nuclei (AGN) or gamma-ray bursts (GRBs), could be the culprits.

When they impact Earth's atmosphere or the Moon, they produce cascades of trillions of secondary particles. The equivalent energies of these collisions extend beyond those that can be studied with the Large Hadron Collider.



The cosmic-ray spectrum, extending over 8 orders of magnitude in energy and 24 orders of magnitude in flux. The energies probed by SKA-EAS and SKA-lunar are shown. These are compared to the centre-of-mass energies of the collisions (top axis). Image credit: T. Pierog et al (EPJ W 89 (2015) 01003; T. Huege, C.W. James.

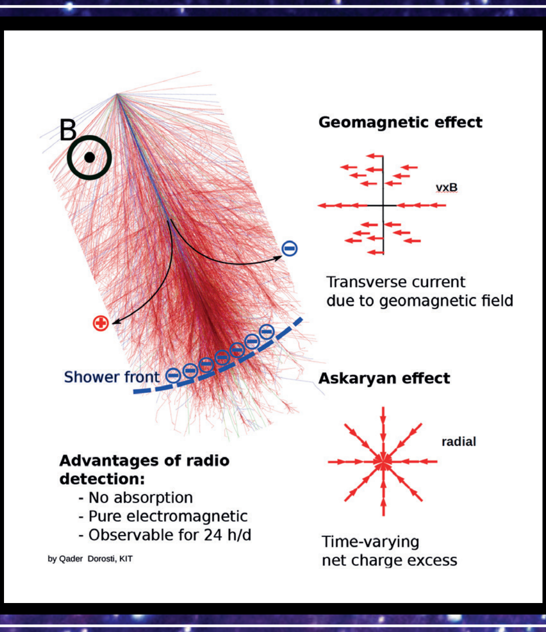


Diagram of the two radio emission mechanisms: the geomagnetic effect (dominant for cosmic ray interactions in the atmosphere) and the Askaryan effect (dominant for lunar interactions). Image credit: T. Huege.

Radio emission

When a cosmic ray interacts, its energy is converted to mass, producing a range of exotic secondary particles. These collide to produce still more particles, and the process continues until the energy of the cascade has been exhausted.

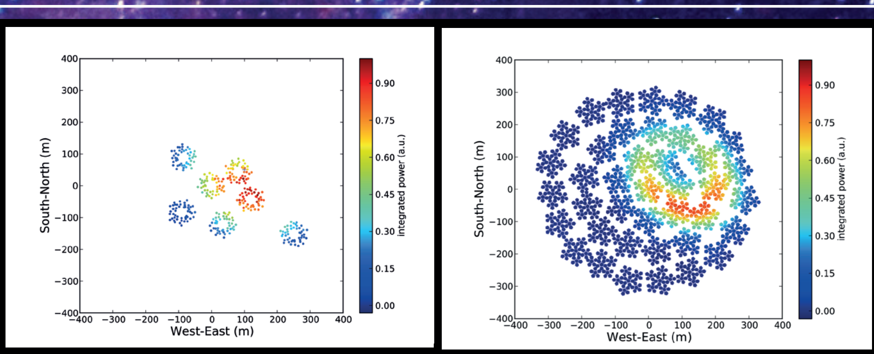
Askaryan effect: As the cascade progresses, electrons in the surrounding medium are knocked loose from their atoms and entrained into the cascade. This leads to an excess negative charge that rapidly builds up and then disappears, producing a sub-microsecond burst of radio waves – Askaryan radiation.

Geomagnetic effect: If a cascade occurs in the Earth's magnetic field, positive and negative particles – particularly the lighter ones; electrons and positrons – will be deflected in opposite directions. Due to their opposite charges, these particles also radiate coherently - geomagnetic radiation.

The two radiation mechanisms have different polarisation signatures, which can interfere to produce a unique pattern on the ground (see figure).

Ultimate precision – EAS

To study Extensive Air Showers (EAS), the High Energy Cosmic Particles group will install an array of hundreds of particle detectors in the SKA1-low core. These will detect secondary particles from cosmic-ray interactions in the atmosphere, and capture voltage data at maximum time resolution from each antenna. Each event will be visible to thousands of antennas, measuring the unique radiation pattern of each cascade with ultimate precision, and allowing precise reconstruction of the properties of the cosmic rays and neutrinos.



Simulated radio footprint of a cosmic-ray event as viewed by LOFAR (left) and SKA1-low (right), showing the increase in precision offered by the SKA's incredible antenna density in the core region. Image credits: A. Zilles, S. Buitink, T. Huege, EPJ Web Conf. Volume 135 (2017) 02004

Extreme energies – lunar

Cosmic rays at the very highest energies (above 10^{19} eV) will produce pulses of radiation so strong as to be visible from the distance of the Moon. The High Energy Cosmic Particles group aims to use the entire visible surface of the Moon as a 20,000,000 km² particle detector to catch these rare ultra-high-energy events. Observations with SKA1-low will cover the Moon with phased-array beams to search for nanosecond-scale pulses.

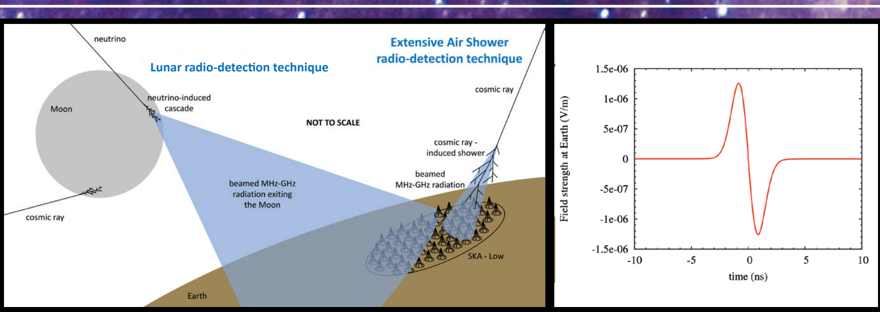
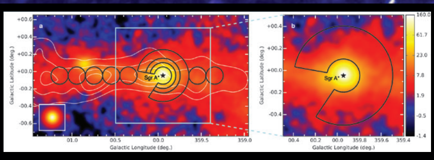


Illustration of the Lunar and Extensive Air Shower radio-detection techniques (left). In the former, a cosmic-ray or neutrino impacts the Moon, generating radio emission in a cone. The radiation can escape the Moon and be detected on Earth as a few-nanosecond burst (simulation shown on right). Image credit left: J. Alvarez-Muniz, right: C. W. James

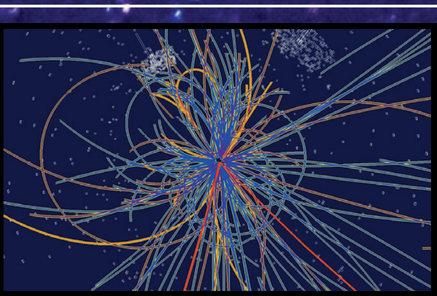
Science Goals



The Galactic Centre revealed in TeV gamma rays by the High Energy Stereoscopic System (HESS). Such gamma rays are expected from cosmic-ray interactions with the interstellar medium, which produce pions and, hence, gamma rays. Image credit: HESS Collaboration, Nature 531 (2016)476 (sourced from arXiv: 1603.07730).

Galactic cosmic rays

Measuring radiation patterns with the SKA will allow the cosmic-ray composition – protons, helium etc. up to iron – to be resolved. This encodes critical information about how Galactic accelerators run out of power, and the transition to extragalactic sources.



Simulation of a proton-proton collision at the LHC. The centre-of-mass energy – critical for creating new particles – is 13 TeV. The equivalent energy for cosmic-ray collisions can reach up to 500 TeV, allowing the study of new physics unreachable by terrestrial colliders. Image credit: CERN.

High-energy particle physics

The extreme energies of cosmic-ray collisions also allow the study of particle physics at energies unreachable at the Large Hadron Collider. Radiation patterns of particle cascades will be searched for signs of new physics beyond the Standard Model.

The nearby active galaxy Centaurus A, viewed at multiple wavelengths. Left: a composite image of the galaxy itself, in optical, radio, and x-rays. Right: the full extent of Centaurus A's giant radio jets,which are outflows from the supermassive black hole in the centre of the galaxy. Such AGN are prime candidates for accelerating the highest-energy cosmic-rays. Image credit: (LEFT) X-ray – NASA, CXC, R. Kraft (FfA), et al.; Radio – NSF, VLA, M. Hardcastle (U Hertfordshire) et al.; Optical – ESO, M. Rejkuba (ESO-Garching) et al. https://apod.nasa.gov/apod/ap080110.html. (RIGHT) Ilana Feain, Tim Cornwell & Ron Ekers (CSIRO/ATNF). ATCA northern middle lobe pointing courtesy R. Morganti (ASTRON), Parkes data courtesy N. Junkes (MPIfR).

Extragalactic sources

At the very highest energies, the paths of cosmic-rays will be only slightly bent by cosmic magnetic fields, so their arrival directions will point to their origin. The measured properties of lunar events will be used to reconstruct these directions, and point towards the source of extragalactic cosmic rays.

SKA SQUARE KILOMETRE ARRAY

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