LOFAR AS A COSMIC RAY DETECTOR

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In the coming years, a new radio telescope named *Lofar* is to be built in the Netherlands with baselines over 100 km. Its unconventional design will enable it to monitor the entire sky simultaneously at high time resolutions, making it an excellent test case for the detection of radio signals from cosmic ray air showers. A prototype station, coinciding with the existing cosmic ray experiment *Kascade*, had been erected earlier to test the hypothesis of coherent synchrotron radiation from air showers. Now that the initial tests with this *Lopes* array prove to be successful, we will use the Lofar telescope in various observation modes to map the cosmic ray spectrum up to 10^{22} eV.

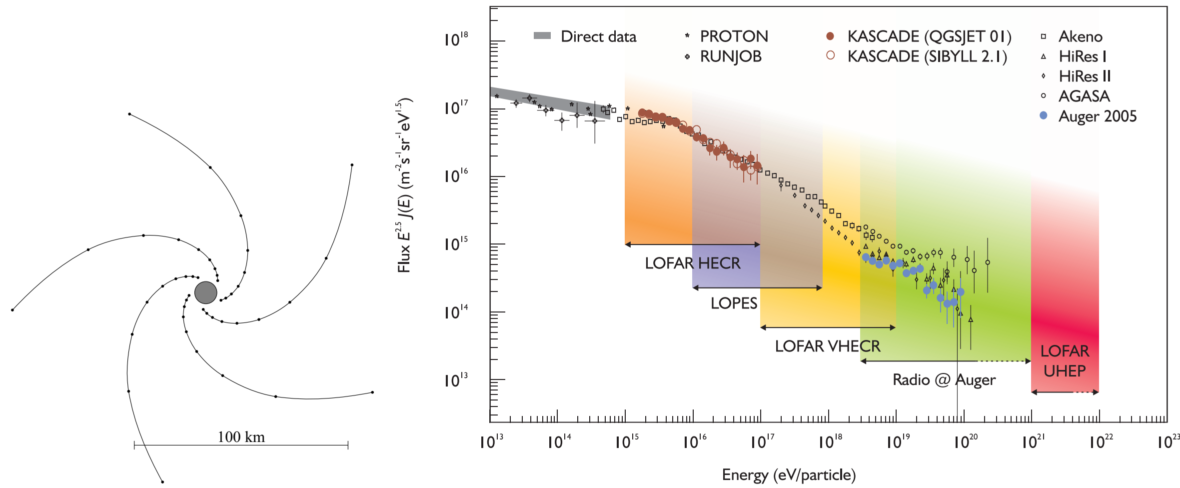
1 The Lofar telescope

A Dutch consortium, headed by ASTRON (The Netherlands Foundation for Research in Astronomy), is building a new radio telescope which is based on an array consisting of simple dipole antennas [1]. This telescope, *Lofar* (Low Frequency Array), will consist of a core of several kilometers in diameter, containing 3100 antennas; and 45 remote stations with a diameter of 100–200 m with 96 antennas each. The total extent of the array will be $\sim$ 150 km; c.f. figure 1a. The total bandwidth of 30–240 MHz is covered by two types of antennas, which are tuned to 30–80 MHz and 110–240 MHz, respectively. Combining the signals of these antennas will be done using software rather than hardware, making the entire telescope incredibly flexible and versatile compared to its predecessors. Lofar development is currently in its final test phase, with the first antennas in the field.

There are four astrophysical 'key projects' within the Lofar science case, three of which propose to observe astronomical objects. The first project, and also the main reason why Lofar was conceived, involves the *age of reionization*. It is believed that at redshifts between 6 and 12, the then neutral hydrogen in the universe was ionised by the radiation from the newly formed stars and galaxies: the redshifted hydrogen line from that epoch is visible in the Lofar frequency range. The 'clumpiness' of the H and H^+ regions would provide information on the formation of the first galaxies.

A second Lofar goal will be to carry out *large-sky surveys*. Deep surveys of the accessible sky at several frequencies will provide catalogues of radio sources for investigating fundamental areas of astrophysics, such as (clusters of) galaxies and the formation of massive black holes. As these surveys will probe unexplored parameter space, it is likely that they will unveil new phenomena.

The large, instantaneous beam and high time resolution will make Lofar uniquely suited to monitor a large fraction of the sky simultaneously. This would allow an unbiased survey of *radio*



a) b)

Figure 1: a) Schematic layout of the Lofar array. The *compact core*, the grey area with a diameter of several kilometers, will be poulated with ~ 3000 radio antennas. Further away are smaller stations (the black dots), which span ~ 200 m. b) Overview of the various cosmic ray observation modes for Lofar and connected experiments. It is foreseen to cover the entire energy range from 10^{15} to 10^{22} eV.

transients for the first time, providing information on time scales ranging from seconds to many days, on sources from extragalactic GRB afterglows to exo-planets.

The fourth project addresses the study of high energy cosmic rays, which will be discussed in the remainder of this paper.

2 Air shower detection with radio antennas

The development of digital radio telescopes such as Lofar has recently initiated a wave of renewed interest in the coherent radio emission from cosmic ray air showers [2]. This phenomenon was originally predicted by Askaryan [3] and confirmed by Jelley et al. [4] using an array of simple radio antennas. Though the phenomenon has been experimentally reconfirmed lately [5], the details of the exact mechanism remain unclear. It is believed that the trajectories of charged particles in an air shower, predominently electron–positron pairs, are slightly curved by the Earth's weak magnetic field. This gyrating motion will produce synchrotron radiation, which is emitted in a narrow cone in the direction of motion of the particles. Since the Lorentz-contracted thickness of the layer of particles travelling through the atmosphere is only a few meters, this radiation is thought to be coherent at frequencies up to ~ 150 MHz [6]. Obviously, there are more effects playing a role, such as a Čerenkov component leaking into radio wavelengths, and transition radiation from variations in atmospheric density.

As a proof-of-principle experiment, the Lopes array or *Lofar Prototype Station* was erected [7]. For simultaneous data acquisition of particles and radio emission, Lopes is triggered by the Karlsruhe Shower Core and Array Detector (Kascade). Since the beginning of 2004 we have recorded events between 10^{16} and $10^{17.9}$ eV, about one in thousand of which are also seen by our radio antennas. There is a clear correlation between the muon number of the shower (as measured by Kascade) and the radio pulse height (as measured by Lopes) [5]. See also elsewhere in these proceedings [8].

There are several advantages of detecting air showers in radio. First of all, the antennas themselves are very cheap and easy to deploy: for Lofar, the cost of a low band antenna is aimed at under one hundred euros. Furthermore, radio waves have practically no attenuation in air: this allows us to see an integral signal over the shower evolution, instead of the footprint only. Furthermore, contrary to for example Čerenkov or fluorescence detectors, radio antennas have duty cycle which is nearly 100%. All in all, radio antennas could be a valuable addition to existing and future cosmic ray experiments.

3 Air shower observation with Lofar

With the principle of radio detection confirmed, we now look to Lofar to span a wider energy range. Lofar's large sky coverage and high time resolution make it ideally suited for the study of short, unpredictable phenomena like cosmic ray events. Unfortunately, the Lofar setup as shown in figure 1a is not optimised for cosmic ray detection, because its applications are mostly in the field of astronomy. The array will still span nearly 100 km^2, however, and will be densely populated, making it sensitive to the signals from air showers in the range of 10^{15} to 10^{19} eV. One of the major differences with Lopes is that we cannot rely on an external trigger for cosmic ray detection. Various trigger scenarios have been designed for different energy scales, which will be discussed in detail below. An indication of the energy ranges covered is shown in figure 1b.

For energies between 10^{17} and 10^{19} eV, the produced radio pulse is bright enough to be picked up by individual antennas. A trigger will then monitor the signals of all antennas continuously. Whenever a certain detection threshold is passed by a number of antennas close together within a short time interval, a microsecond of data of all antennas within an area of up to a few km^2 is saved. Further central processing may discard events if, for example, the signal appears to originate from within the station. Further analysis of events and determination of the shower parameters is done offline.

For the lowest energies, at 10^{15} to 10^{17} eV, radio pulses from air showers are too weak for individual antennas to be picked up. By forming a wide beam with multiple antennas, however, the detection threshold can be lowered — at the cost of sky coverage. Therefor, the trigger as described above will also be applied to *beamed* data sets. This could be done either in a dedicated experiment, or, due to the flexible nature of Lofar, we could "piggy-back" our trigger inside the beam of a running experiment of the transient project.

An interesting secondary motive might be the study of the interaction of cosmic rays and lightning. It is believed that, by creating ionized paths through thunderclouds, cosmic rays might be responsible for some of the lightning discharges in the atmosphere. During thunderstorm conditions, we therefor switch to a mode where longer data snapshots are collected, which would include signals from possible lightning discharges following the air shower signal [9].

There are plans to put up radio antennas inside the Pierre Auger array as well. This project would extend the energy range of radio detection of cosmic rays to $\sim 10^{21}$ eV, and provide valuable complementary data on shower evolution.

4 Detection of cosmic particles in the Moon with Lofar

For the very highest energies of 10^{21} eV and above, beyond the GZK cut-off, the flux of cosmic ray events is too low for a detector with an effective area of 100 km^2 to expect a significant number of events. In a recent publication however [10], Scholten et al. consider the possibility of using the entire volume of the Moon as a detector for both cosmic rays and neutrinos. Since our satellite has no atmosphere, cosmic rays slam right into the surface. Inside the lunar regolith, a 'Moon shower' would start, giving rise to Čerenkov radiation which, depending on angle and wavelength, can traverse the Moon–vacuum boundary and emerge from the surface on the other side. The flash would be very brief, but bright enough to be visible from Earth. The optimal wavelength to look for this phenomenon would be around 300 MHz. This approach could be used for the detection of neutrinos as well, which would have a reasonable chance of interaction when traversing the Moon.

Calculations show that the visible cosmic ray flux would peak between 10^{20} and 10^{21} eV (c.f. figure 1b). Given the huge size of the Moon compared to other, ground-based experiments — the apparent surface of the Moon is nearly $10^7\,\mathrm{km}^2$ —, the effective area will greatly exceed that of any cosmic ray experiment, existing or proposed. In fact, due to this huge collecting area, the existence of the GZK cut-off could be proven or disproven after as little as a month of dedicated observation of the Moon with Lofar. To test the theory of lunar flashes, a 100-hour pilot project has been initiated using the Westerbork Synthesis Radio Telescope (WSRT).

5 Conclusion

With radio detection of air showers now firmly established by Lopes, Lofar hopes to contribute to the physics of air showers in the range of 10^{15} to 10^{19} eV. Placing radio antennas at the Pierre Auger site as well might provide this project with an additional, independent detection method. Finally, the exciting possibility of using our Moon as a particle detector may deliver a cosmic ray spectrum up to 10^{22} eV and unveil the GZK cut-off after only a month of observations.

Acknowledgments

This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)'.

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