HiSPARC

a view from the bottom

J.W. van Holten[†]

NIKHEF, Amsterdam NL

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[†] e-mail: v.holten@nikhef.nl

1. Introduction

In June 2004 the european award for innovation of the Altran Foundation was awarded to the HiSPARC project for its approach to outreach and education in science and technology [1]. In the best of academic traditions this project has been initiated to integrate research and teaching: its starting point is an important problem in fundamental science, the solution of which obliges the participants at all levels to acquire the necessary scientific background, master scientific methods and develop technical skills. Only this time the teaching and research are not restricted to the university level, but include many participants at the level of high-school science classes. In this article I will address both the educational and scientific issues involved.

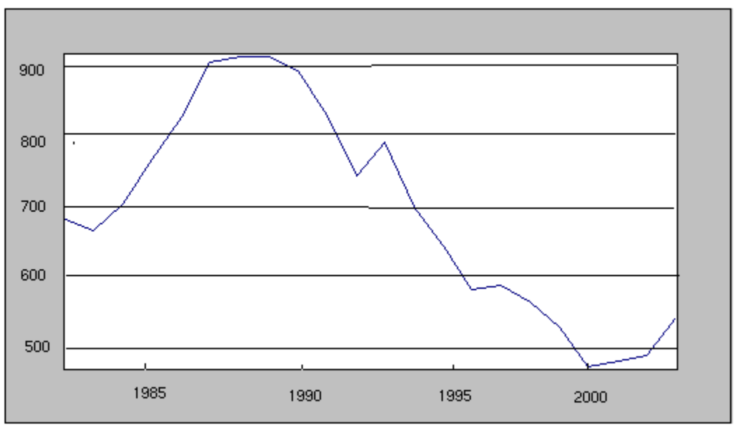

Fig. 1: Number of first-year physics students in the Netherlands

2. Science education and the public image

In fig. 1 the number of new physics students in the Netherlands is plotted for the years 1980-2004. The present number is just above 500, down from more than 900 in the middle of the 1980's. Although there are regional differences, the downward trend is a general one in western Europe. It is not only observed in physics, but also in other hard sciences, like chemistry and mathematics; it is partly offset by an increase in the life sciences, but even including demographic factors, the enrollment in science as a percentage of all first-year university students is down significantly w.r.t. the situation 20 years ago.

In the year 2000 the European governments at a meeting in Lisbon pledged to turn Europe in one of the worlds leading economies by 2010, in particular by heavy investment in R & D. So far they have fallen way short of their targets, and it is unlikely that the ambitions will materialize.

One problem is the shortage of academically qualified scientists and engineers. This is not only due to demographic developments, the number of new-born children having dropped steadily all over Western Europe since the 1960's; a number of other factors contribute as well. Among these is the public image of science: science is perceived as difficult and abstract, it has no particularly high social status –in some parts of society it is sometimes viewed with suspicion– and the scientific professions are not seen as glamorous and exciting. In addition, it has become increasingly difficult for science to attract the interest of teen-age children amidst a profusion of other attractions. There is strong competition for example from the entertainment business, for whose video clips and computer games this age group represents a billion-euro market. For all of these reasons we have found that at the time in their life at which young people have to make educational and career choices, they often have no well-informed view of the scientific and technical professions, and are inclined to ignore them even if they have the talents to become successful in them.

If this trend is to be reversed, we need to develop alternative ways to inform young people about science, its importance and excitement, and the personal and professional satisfaction that can be derived from it. This provides the extrinsic motivation for the HiSPARC project. In HiSPARC young people at high-schools and universities collaborate with teachers and research scientists to investigate the riddle of ultra-high energy (UHE) cosmic rays. This way they acquaint themselves with science and the scientific environment directly. For many of them this is a real eye-opener. The way people with different backgrounds: theoretical, experimental and technical, co-operate and interact to get a project going, collect data and interpret the results is a strongly motivating experience.

The choice of cosmic ray physics is to some extent arbitrary. It is in part a result of the background of the people who initiated it. The scientific case for this topic is made below. Here I should just point out the many

different basic aspects of physics which can be covered in such a project. A very incomplete list includes at least the following topics which have to be mastered:
- the structure of matter and radiation;
- conservation laws and relativity;
- particle detection and scintillating materials;
- electronics, Global Positioning System;
- signal analysis and statistics;
and many more. Let me now turn to the science.

3. Cosmic ray physics

The intrinsic motivation for the HiSPARC project comes from the scientific interest: the investigation of the nature, flux and origin of ultra-high energy cosmic rays. UHE cosmics are actually subatomic particles, presumably protons or heavier nuclei, with energies of 10^{17} eV or more.

The story of cosmic ray research really started in the early 20th century with the work of Theodor Wulf, a german jesuit priest, who for a number of years taught physics at a jesuit college in Valkenburg, in the southern part of the Netherlands. Around the turn of the 19th-20th century it was known that radiation from radioactive minerals, as discovered by Becquerel a decade before, could discharge an electroscope. The rate of discharge is a measure for the intensity of the radiation. In order to make such measurements precise and reproducible, Wulf designed a much improved instrument.

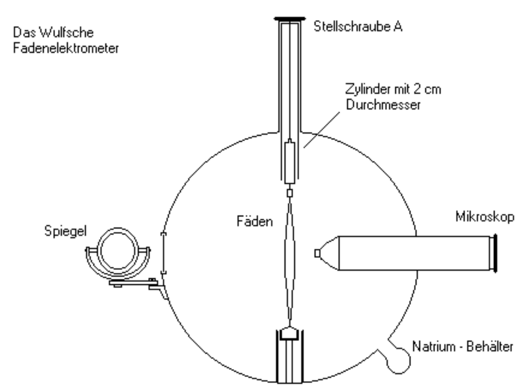

Fig. 2: Wulf electrometer.

This instrument was of such a high quality that it was actually taken into production by a manufacturer of scientific instruments in Germany and sold to a considerable number of research institutes across Europe.

Once he had the instrument, Wulf began to take measurements of natural radiation levels, starting at the college. Then he went underground: in the Valkenburg area there is an extensive network of human-made caverns, where limestone rocks have been cut for building industry. Acting on the theory that the natural radiation background came from radioactive minerals in the earth, Wulf expected an increase in radiation intensity when he took his electrometer down into the caverns. To his great surprise however, he found a marked *decrease* in levels of radiation below the earth's surface. This puzzled him to the extent, that he then asked assistance from a colleague at the university of Paris to arrange for him to be allowed to make measurements on the Eiffel tower.

The request was granted, and Wulf actually performed a series of measurements high up on the Eiffel tower. Although the results were not conclusive as to an increase in radiation levels, they certainly did not show any decrease. Therefore Wulf conjectured that the natural radiation background comes from the top of the atmosphere, presumably from space. Wulf described his measurements in a number of scientific papers, among them one that was published in the Physikalische Zeitschrift in 1909 [2].

In the following years, more measurements using Wulf electrometers were carried out, some on high mountains in the Alps, all suggestive of Wulf's hypothesis, but none with sufficient statistics to draw definite conclusions.

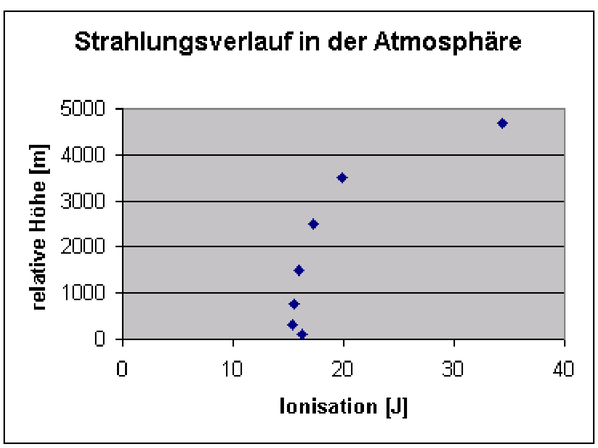

Fig. 3: Intensity of natural radiation levels as a function of altitude, determined by V. Hess (1912).

Then in 1911 Victor Hess, a young physicist at the university of Vienna in Austria, took up the challenge. In a series of hot-air balloon flights he rose to a height of nearly 6 km, carrying one of Wulf's electrometers with him [3]. On these flights he took data which finally established beyond reasonable doubt that the intensity of natural background radiation grew with increasing altitude, and that the radiation had an unknown extraterrestial origin.

From his measurements, displayed in fig. 3, it also becomes clear that a marked increase in intensity of the ionizing radiation only occurs at altitudes above 4000 m, which is why no conclusive evidence could be established by any of the earlier experiments. Many years later, in 1936, Hess was awarded the Nobel prize for these observations.

Many important discoveries have been made using cosmic rays as a source of high-energy particles. These include for example the discovery of anti-matter, in the form of positrons, by Carl Anderson in 1932; and in 1947 the discovery by Powell of a new family of subatomic particles, represented by the muon, a substantially more massive type of electron. However, the flux, the energy spectrum and the origin of cosmic rays proved a riddle which has not been solved completely to the present day.

Progress on the nature of the atmospheric background was made in the 1930's by Pierre Auger, who carried out measurements in the laboratory of Jean Perrin at the Jungfraujoch in the Berner Oberland [4]. Auger discovered, that ionizing radiation in the atmosphere occurred mostly in bursts of radiation covering a large area, sometimes several hundreds of square meters. This result was interpreted correctly as indicating that the atmospheric radiation consists actually of secondary particles produced in the scattering of very high-energy particles from outer space off atomic nuclei high up in the atmosphere. These bursts of secondary (or tertiary, or n-ary) particles were called *air showers*. Air showers only give indirect information about the nature and energy of the initial primary cosmic particle.

To understand the nature of the primary radiation one either has to infer the energy and momentum of the initial incident particle from a measurement of the total impact of secondary products, or one has to try to measure the incident radiation directly by doing an experiment in the highest levels of the atmosphere, 20-40 km above the surface of the earth.

The second option was actually realized first in unmanned high-altitude balloon flights, especially in the years immediately after the second world war; later the development of high-energy accelerators started to provide manmade sources of high-energy particles for studying the nature and interactions of subatomic particles, and interest in balloon-borne experiments diminished. Nowadays there is the possibility of carrying experiments on board of space craft; this is particularly useful for studying the large numbers of energetic charged particles emitted by the sun, known as the *solar wind*. Nevertheless, as I will explain there is still an important scientific case for ground-based air shower detectors. This is where the HiSPARC experiment tries to make a contribution.

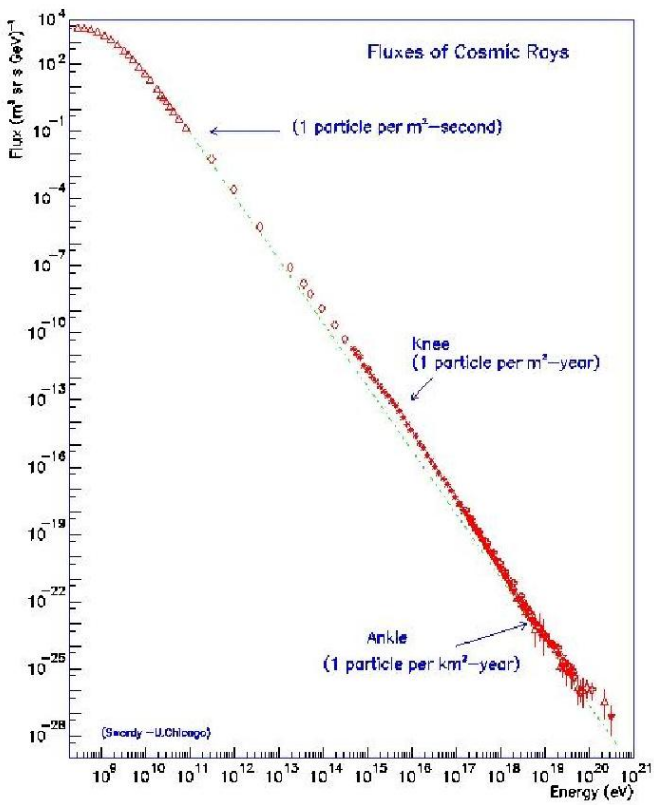

Fig. 4: Incident flux of cosmic particles as a function of energy

4. The cosmic-ray spectrum

During the second half of the 20th century, several generations of cosmic-ray observatories have mapped out a large part of the spectrum of charged particles bombarding the earth's atmosphere from outside. The most recent ones include experiments at Haverah Park [5], Yakutsk [6] and the AGASA experiment in Japan [7]. The results of these experiments are summarized in fig. 4. Evidently, the majority of particles entering the atmosphere have energies up to 10^9 eV, or 1 GeV. These include protons, α-particles and heavier nuclei, mostly from the sun.

At energies between 10 GeV and 10^6 GeV per particle, the flux decreases as a power law:

$$\Phi(E < 10^6\,\mathrm{GeV}) \propto E^{-2.7}. \tag{1}$$

The flux of particles with energies of 10^6 GeV on the top of the atmosphere is very small: only about 1 particle per square meter per year. Data for even higher energies show a power-law behaviour with a somewhat steeper slope:

$$\Phi(E > 10^6\,\mathrm{GeV}) \propto E^{-3.1}, \tag{2}$$

which holds up to particle energies of about 10^{10} GeV. There the spectrum levels off and there is only a relatively small set of data for energies above 10^{10} GeV; the highest energy ever observed is 3×10^{11} GeV, or 3×10^{20} eV.

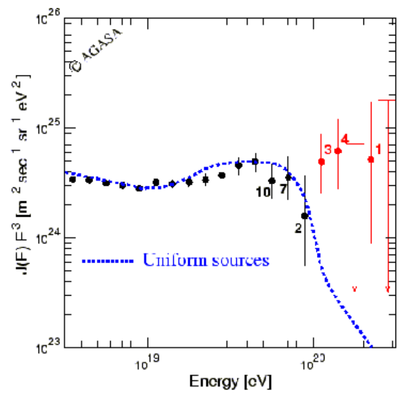

Fig. 5: High end of the cosmic ray spectrum

A most interesting region of the spectrum is the high-energy end, with particle energies of more than 10^{17} eV. Fig. 5 shows a comparison of data with theoretical expectations by the AGASA expriment in Japan. Although the flux is extremely low here, with less than one particle per year per square kilometer hitting the earth's atmosphere, the AGASA measurements seem to hint that the flux may still be larger than expected. In fact, on theoretical grounds we expect a steep decrease around 3×10^{19} eV, known as the GKZ limit at which high-energy nucleons can scatter inelastically from the cosmic microwave background [8]. This mechanism should deplete the spectrum of protons (and heavier nuclei, if any) above the GKZ limit, and cause a pile-up at energies slightly below it, as indicated by the blue dotted line in fig. 5. The data are inconclusive, but do not rule out a continuation of the spectrum above the GKZ limit.

5. The origin of UHE cosmic rays

The cosmic rays we discussed previously are charged particles like protons and heavier nuclei, from helium to iron. In addition there are also high-energy gamma rays, which can produce airshowers. High-energy neutrinos are certainly present in the universe as well. Neutrinos are very light, very weakly interacting neutral particles produced mainly in nuclear and radioactive transformations, such as go on in the interior of stars. About the spectrum of cosmic neutrinos virtually nothing is known at present.

The origin of the various species of very high-energy cosmic particles has only been partially established. Low-energy particles in the solar wind obviously originate in the outer layers of the sun; in contrast, solar neutrinos come directly from the core. Higher-energy cosmic rays, up to the knee in the spectrum near 10^{15} eV, have their origin in our own galaxy. This can be inferred, because the magnetic field of our galaxy, though weak, does not allow charged particles with less energy to escape. Most of them are thought to be produced in supernovae, the impressive events in which a massive star collapses under its own weight, after it exhausts its nuclear fuel. Most of the energy released by the implosion is actually radiated in the form of neutrinos, but gamma rays and high-energy charged particles are produced in large numbers as well. The rate of supernova implosions and the flux of high-energy particles released correlates remarkably well with the measured flux of cosmic rays on earth.

The source of the most energetic cosmic rays is not known with any certainty. As the energy of these particles is sufficient to escape galactic magnetic fields, they can traverse the universe over cosmic distances. Therefore the events with energies close to the GKZ cut-off observed on earth could be due to particles that originate in distant galaxies.

Many if not all large galaxies are thought to harbor gigantic black holes in their centers, some of which are active in accreting matter from the galactic core surrounding them. In this process very large, extremely energetic jets of particles can be created, extending far beyond the galaxy itself. These jets are certainly also sources of very-high energy cosmic rays, produced in shock waves such as can be observed at the end of the large jet in the galaxy M87 shown in fig. 6.

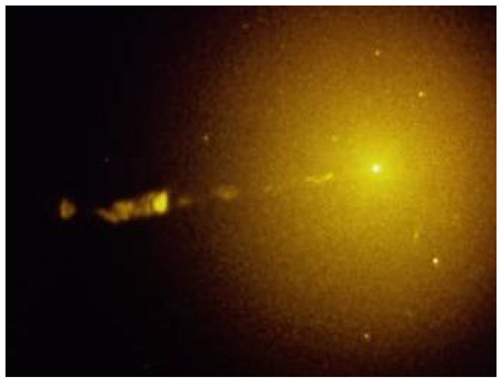

Fig. 6: Jet originating in the galaxy M87.

For particles with the very highest energy, above the GKZ cut-off, the source can not be very far away on a cosmic scale. But no object capable of producing them has been identified so far. It could be that they result from the interactions of other unknown particles in the neighborhood of our solar system, but at present such questions remain unanswered. What is needed is more data on cosmic rays, their energies and the directions they come from.

6. Observing air showers

To investigate the highest-energy cosmic rays, it is not feasible to carry out observations in space, as that would require a detector with an area of at least several square kilometers, which would be difficult to keep in place and vulnarable to interplanetary dust and small meteorites, to name just a few of the obstacles. The best strategy to observe rare high-energy particles is by having a detector with as large a volume as possible, in which the incoming particles deposit their energy, after which the total energy is measured by reconstructing the tracks of the most energetic secondary particles; such a detection technique is called calorimetry and it is a standard procedure in particle physics with accelerators. For cosmic rays the best calorimeter is the atmosphere itself: it has a large volume, and provides a sufficiently large target for the incoming particle to interact with and produce secondary particles, forming the air showers. By observing the particles in the airshower, measuring their number, their energy and their arrival times, the energy and direction of the incoming cosmic particle can be reconstructed.

The airshowers have the structure of a tree as in fig. 7, starting with a single particle, with secondary particles branching in all directions, until a maximal number of particles is present at some distance X_{max} from the initial collision; after this point on average the particles no longer have sufficient energy to create new particles, and more and more particles are scattered or absorbed, with the result that the shower thins out and after a while stops to be observable.

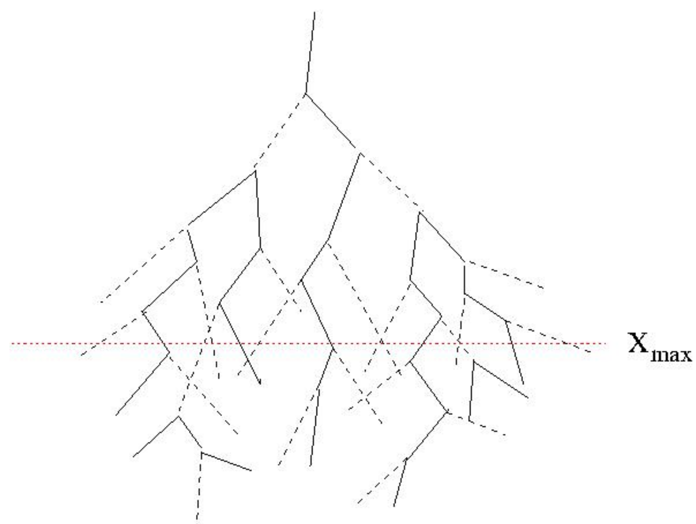

Fig. 7: Schematic air shower development

The various parameters like the distance X_{max} and the number and type of secondary particles tell us something about the primary cosmic particle which started the shower. For air showers produced by cosmic protons of energy 10^{19} eV, X_{max} lies close to sea level. This greatly facilitates the study for such ultra-high energy showers.

To observe a shower, there are several techniques which provide complementary information. The charged particles like muons and electrons can be observed with an array of scintillation detectors. A scintillation detector consists of a plate of special plastic material which produces light whenever a charged particle passes through it. This light is guided to a photomultiplier, a device that detects the light and produces an electric current. The current is measured and indicates the amount of light produced. In this way the energy of the particle that passed through can be determined.

The advantage of this type of measurement is, that the detectors are relatively inexpensive and easy to make. This is why the HiSPARC project has opted for this kind of measuring technique. Other approaches are possible. High-energy charged particles can also be detected with water Cherenkov detectors. These consist of a sealed tank with a volume of several cubic meters containing clean and clear water. As the speed of light in water is less than that in vacuum, a charged particle can fly through the detector at a speed larger than that of light in water. It then produces a special kind of light, focussed like a shockwave, called Cherenkov light. By observing the Cherenkov light with photomultipliers one can observe not only the passage of a charged particle, but also its direction of motion. Reconstructing the tracks of particles from the same air shower in a all detectors which were hit by the shower provides information on the number of particles in the airshower, and the direction from which the airshower came. This technique is used in the Pierre Auger experiment [9], the largest air shower detector ever constructed, consisting of 1600 water Cherenkov detectors, which will be inaugurated in the fall of 2005 in the Pampa Amarilla in Argentina.

In addition to the observation of the charged particles produced in an air shower, it is also possible under ideal conditions to observe a very faint light produced by the air molecules along the path of the air shower, which for this purpose can be considered as an extended electric current running through the atmosphere. This technique has been developed by the Fly's Eye and Hires experiments [10], which observe this fluorescent light in clear moonless nights in the desert in Utah, in the U.S. with the help of an array of sophisticated composite mirrors, reflecting the light on photomultipliers. The nice feature of this difficult and delicate detection technique is, that it allows one to follow the development of the showers in the atmosphere, giving good indications of the direction, the position of X_{max} and the total number of particles in the shower.

7. HiSPARC

HiSPARC is a project to observe ultra-high-energy cosmic rays with a ground-based scintillation detector network [11]. A special aspect is, that the detectors are built by high-school students and placed on the roofs of their schools. At present five regional clusters of detectors are being developed in the Netherlands, in the areas of Amsterdam, Groningen, Leiden, Nijmegen and Utrecht.

Fig. 8: High school students building a scintillation detector for cosmic rays.

In each cluster a university or research institute acts as the local co-ordinator, but data are collected centrally[1] at NIKHEF, the national institute for particle physics. All participants have access to the data and can use them for either scientific or educational purposes.

Fig. 9: Pair of HiSPARC scintillation detectors.

The ultimate aim is to have in each cluster at least 15-20 detector stations in an area of the order of 100 km^2. Presently between 30 and 40 high-schools are participating, but the number is growing.

[1]With the present exception of NAHSA, the Nijmegen cluster, which has been collecting its own data already since an earlier time.

The funding for the project comes from various sources, both public and private. A major boost for the project has been the selection of HiSPARC for the 2004 european innovation prize of the Altran Foundation in Paris. Presently the Altran Foundation is strongly supporting the project by helping with an improved detector design, data formatting and storage, and setting up a professional organization.

The participating schools benefit form direct access to scientists and university laboratories; also by becoming partners in a network which allows the common development and exchange of educational materials and teaching practices; and finally HiSPARC offers a rich source of research projects, which are part of the requirements for Dutch high-school science graduation exams. The scientific institutes and universities collect valuable scientific data, and communicate directly with teachers and prospective students. In addition, the HiSPARC project offers a beautiful opportunity for disseminating scientific knowledge to the public at large.

8. LOFAR

With 5 or more clusters of cosmic ray detectors in the Netherlands, and possibly other regions in Europe, it will become possible not only to study the spectrum of cosmic rays with energies above 10^{17} eV, but also to look for correlations between their arrival, both in a single cluster and among different clusters. As the highest-energy cosmic rays are not very sensitive to galactic and intergalactic magnetic fields, and as supra-GKZ energy particles can not come from too far anyway, their direction of arrival should still be correlated quite significantly with their source of origin. Thus one may hope to be able to search for point sources, as has also been attempted by the AGASA experiment [7].

A much improved resolution of the energy and direction of very high-energy cosmic rays may result by linking HiSPARC to the LOFAR observatory. LOFAR is a low-frequency synthesis radio telescope under construction in the Netherlands and the adjacent regions of Germany. It will consist of a large array of clusters of small radiotelescopes, centered around the radio-telescope facility of ASTRON at Dwingelo, as shown in fig. 10.

LOFAR should be able to detect coherent radio emission from a high-energy air shower as it passes through the atmosphere, much like the Hires experiment can see the fluoresecent light [12]. The advantage of LOFAR is, that it can operate 24 hours a day, 7 days per week.

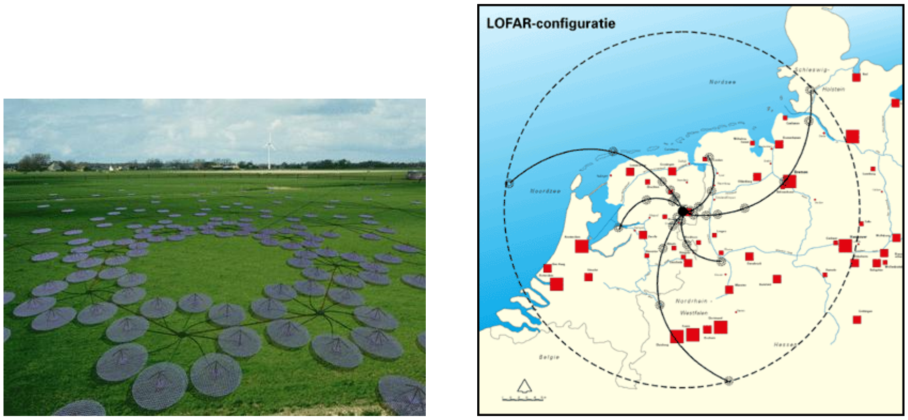

Fig. 10: The layout of the LOFAR radio telescope.

HiSPARC can then be used as a trigger to initiate an air-shower search by LOFAR. Clearly, the time schedules of HiSPARC and LOFAR match very well, and together these instruments could form an excellent new kind of set-up for the detection of high-energy cosmic rays.

9. Conclusions

High-energy cosmic rays form a challenge to our understanding of the universe and the particle physics processes underlying astrophysical phenomena. Data about these processes can be collected using arrays of ground-based particle detectors. The HiSPARC project shows, that such science can be excellently integrated with educational activities, involving high-school science teachers and students as serious partners in research. All parties benefit from such an arrangement.

The quality of the data collected can be much improved, if HiSPARC can be linked in the future to the LOFAR array to detect radio signals of air showers. Another source of interesting complementary information will come from future high-energy neutrino observatories.

At the time of writing, HiSPARC is in the initial stages of building a detector network. Because of the way it is organized this will take considerable time. Even though already now data are taken and analyzed [13], the quality and resolution of the network needs further improvements and additions. We expect that the experiment will run for at least 10 years. From the perspective of education and outreach this is actually an advantage.

HiSPARC is not the first cosmic ray project with educational or outreach components. However, presently it is the largest and most advanced project of this kind in Europe. HiSPARC is building an excellent scientific and educational infrastructure. Its modular set-up allows easy integration of new clusters, which could equally well be located elsewhere in Europe. Sharing discoveries and experiences with others is happening both at the level of individuals and in broader meetings and workshops. By collaborating and pooling resources, this branch of physics can grow into an important new scientific programme across Europe.

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