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Large radio arrays for the detection of cosmic particles

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Abstract

Recent years have shown a flurry of results from the radio detection of cosmic rays, both from dedicated arrays and from measurements using astronomical radio arrays. Detecting the radio emission from cosmic rays as messengers from the ultra-high energy universe has established itself as 'standard detection' method. Based on these successes the radio detection of similarly high-energy neutrinos is gaining traction. I will review the current status of the radio detection in the field of astroparticle physics, highlight future experimental efforts and elaborate on open questions and future experimental challenges.

1 Introduction

The existence of ultra-high energy cosmic rays has been known for over a century. These charged atomic particles arrive at Earth and can be measured through various avenues. Still, the origin of the most energetic particles (EeV = 10^{18} eV energies, order of magnitudes above those reachable by human-made accelerators) remains unknown. In an era of *multi-messenger astronomy* several large experimental efforts target neutrinos, gamma-rays and cosmic-rays to identify the elusive astronomical sources. The radio detection of these messengers plays several important roles.

2 Cosmic rays and cosmogenic neutrinos

The energy spectrum of cosmic rays detected at Earth spans several orders of magnitude in energy. The flux is falling steeply with energy, roughly following a power-law with index -3. This means that the most common cosmic rays are plenty abundant and their origin clear, the Sun. With increasing energy, the flux decreases, still allowing to conclude that many cosmic rays are of Galactic origin. Only at the highest energies the picture is less clear. The flux drops to one cosmic ray per day and square kilometer or less, requiring large detectors to obtain enough statistics. These cosmic rays are not measured directly, but the products of their interaction with the atmosphere. The charged atomic nuclei interact in the atmosphere, creating particle showers extending over large areas. Still, at the highest energies even the largest arrays measure only one event per year. Even though a sizable amount of cosmic rays have been measured, their sources could still not be identified. The reason is two-fold. Since the particles are charged, their trajectories through the universe are bent by magnetic fields and do not directly point back to the sources. Also, the interaction in the atmosphere complicates the identification of the exact charge and arrival direction.

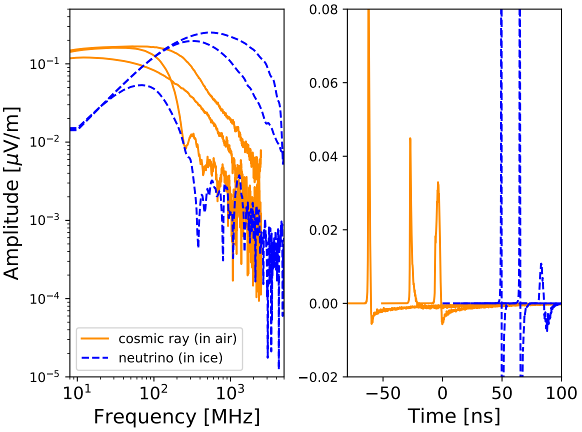

Figure 1. Pulses and spectra of typical cosmic rays (solid) and neutrino signals (dashed). The pulses are both short and bipolar, neutrinos show much higher frequencies. The differences shown are results of a different observer distances with respect to the shower axis.

Likely candidates for cosmic ray acceleration are large objects with strong magnetic fields, such as active galactic nuclei (AGN) or violent explosions such as mergers of neutron stars. In these sources, cosmic rays are not produced alone. Whenever particles are accelerated matter and photon fields are present. Cosmic rays can interact with these and create gamma-rays and neutrinos, where gamma-rays are often absorbed again. The same interactions can happen during propagation when cosmic rays interact with the cosmic microwave background. Detecting the resulting cosmogenic neutrinos would provide a way to directly trace the sources, since neutrinos travel in straight lines and are not absorbed.

3 Radio emission from cosmic particles

When a neutrino or cosmic ray interacts at Earth, they create a particle shower, which is then typically detected by measuring the remaining particles. However, the shower itself also creates a measurable radio signal. Several effects play a role: through the geomagnetic field, the charges

within the shower are separated and a macroscopic dipole is formed that changes as function of time as the shower develops and thereby emits radiation. In addition, the shower front collects electrons from the medium and becomes increasingly negative, which also leads to emission, called *Askaryan emission*. The signal is only detectable when coherent, thus, the shower size determines the frequency content. Coherence of the broadest range of frequencies is reached at the Cherenkov angle, where all emission arrives at the same time.
Cosmic rays have a high enough interaction probability that they develop showers in air, kilometers is scale. Their radio emission therefore contains low MHz frequencies, as shown in Figure 1. Neutrinos in turn, rarely interact per unit matter, so a solid, radio-transparent medium is needed to have some chance to detecting them. In ice, for example, the shower develops much faster, thus, yielding much higher frequencies. Still, the characteristics signature is similar: a non-repeating, bipolar broad-band pulse.

4 Status of the field

The radio detection of cosmic rays has advanced to a standard method. The emission mechanisms have been established beyond doubt and experiments have contributed to composition measurements of cosmic rays.

4.1 Radio detection with dedicated arrays

Several dedicated arrays have been built to show the suitability of radio detection for cosmic rays [1, 3, 2, 4]. These arrays are typically on sparse but regular grids to sample as much flux as possible and simplify detection efficiency calculations. Air showers are detected by either self-triggering, which remains experimentally challenging in places with high RFI contamination, or triggered by particle detectors. The latter reduces the desired cost-effect of relatively cheap radio antennas, but allows for the cross-calibration with standard particle methods. This has shown, for example, that the radio emission is an excellent energy estimator for cosmic rays, subject to very few systematic uncertainties [5].

4.2 Radio detection with telescopes

Distributed astronomical arrays bring a feature that cosmic ray experiments need. Large areas covered with a high density of antennas. Cosmic rays have successfully been detected at the OVRO-LWA [6] and at LOFAR [7]. Especially LOFAR with its high antenna density and hardware buffers has had a significant impact in understanding the radio emission and its capabilities [8]. Measuring cosmic rays with radio telescopes, requires an in-depth understanding of the instrument, often in aspects not probed in astronomical calibrations. This leads to interesting opportunities for co-operation between astronomer and astroparticle physicists [9].

4.3 Radio neutrino experiments

No radio signal of a neutrino has been detected yet. Current neutrino experiments are far too small to stand a chance of detecting the low neutrino flux and have not gone past technology demonstrators [10, 11].

5 Future experiments and open questions

Radio detectors of cosmic rays can now still gain in two aspects: collection area and antenna density. With a larger collection area, the number of high energy events increases, allowing access to a region yet unprobed by the very accurate composition measurement based on the radio emission. The Pierre Auger Observatory is currently instrumenting all of their 1600 particle detectors with additional radio antennas, covering an area of 3000 km^2 on a hexagonal grid of 1.5 km [12]. This will improve the composition measurements of the Auger Observatory, likely providing the most accuracy cosmic ray measurements at the highest energies.

Even larger plans are followed by the GRAND collaboration intending to place 300,000 antennas in a number of clusters in different locations. Thereby covering enough area that they may also be sensitive to the interaction products of neutrinos [13]. GRAND will have to face the challenge of triggering in real-time on the correct pulses, using low-power autonomous stations and restricted data rates. A demonstrator is currently being built. Existing radio arrays may be suitable to help develop efficient self-triggering algorithms, especially when they have cabled infrastructure in place, allowing for high data rates and fast computing. In order to target neutrinos, that may arrive once per 10 km^3 per year or less, self-triggers need to be highly efficient in detecting all neutrinos and at the same time extremely pure, thus rejecting all man-made, natural or other background signals. The hardware of such radio arrays is different to typical radio arrays: the antennas are not cabled, thus relying on GPS timing accuracy between them and the data is not continuously read-out, but only stored following a trigger, typically transferring less than a microsecond of data. Given the power restrictions of autonomous stations, the processing done on station level has to be modest, modern methods of machine learning may play a vital role here.

Also the IceCube Collaboration has decided to pursue radio detection of neutrinos. They intend to build an array of antennas in the ice at South Pole, searching for the radio signal of cosmogenic neutrinos [14]. A first array and demonstrator is being built at Summit Station in Greenland [15]. Here the challenge is to built instrumentation that can withstand polar environments, cope with long polar nights and to understand specific ice properties. Also these arrays will have to self-trigger, but their challenge is smaller as very few background signals are expected to originate from within the ice.

For increasing the antenna density the hopes of the cosmic ray community lie on the SKA. With an antenna density as planned for the core of SKA, one may actually be sensitive enough to image the development of the shower. Similarly to LOFAR, a read-out of the SKA will be triggered by a particle detector signal. This may give access to the particle physics of the shower, such as hadronic interaction processes and relieve tension between different composition estimates [16]. The collection area will, however, not be large for gathering a significant amount of events in the high energy regime. Existing arrays will have already gathered continuously growing data-sets once the SKA starts measuring. The SKA, however, may overtake the other experiments through unprecedented accuracy of single events.

For a long time, it has been tried to detect the radio signal of neutrinos interacting in the lunar regolith by pointing radio telescopes at the moon [17]. While delivering huge exposures, these techniques have comparatively high energy thresholds, thereby probing regions that have been disfavored by other experiments. Additional work is needed to lower the energy threshold in order to become competitive.

One has to note the different requirements for cosmic ray science and radio telescopes. Cosmic ray experiments preferably take data 24 hours per day and need access to the raw data instead of correlated products. In turn, the data rate requirements are very modest, about 1μs are needed per trigger about once per hour per instrumented km^2. These somewhat orthogonal requirements, complicate it to build instruments that can be used for both science cases.

6 Conclusions

The astroparticle physics community is embracing the radio detection as promising technique for neutrinos and high accuracy cosmic ray measurements. Stand-alone arrays are planned and may be exploited for other purposes. The same is true for the other direction. If technological infrastructure admits, most dedicated astronomical arrays can be and are used to measure cosmic rays, which provides additional science return and well-understood calibration signals.

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