The HiSCORE experiment and its potential for gamma-ray astronomy

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Abstract. The HiSCORE (Hundred*1 Square-km Cosmic ORigin Explorer) detector aims at the exploration of the accelerator sky, using indirect air-shower observations of cosmic rays from 100 TeV to 1 EeV and gamma rays in the last remaining observation window of gamma-ray astronomy from 10 TeV to several PeV. The main questions addressed by HiSCORE are cosmic ray composition and spectral measurements in the Galactic/extragalactic transition range, and the origin of cosmic rays via the search for gamma rays from Galactic PeV accelerators, the pevatrons. HiSCORE is based on non-imaging Cherenkov light-front sampling with sensitive large-area detector modules of the order of 0.5 m². A prototype station was deployed on the Tunka cosmic ray experiment site in Siberia, where an engineering array of up to 1 km² is planned for deployment in 2012/2013. Here, we address the expected physics potential of HiSCORE, the status of the project, and further plans.

1. Introduction

The still unsolved question of the origin of cosmic rays can be addressed by a multi-messenger approach including directional information (gamma rays or neutrinos) as well as information of the chemical composition and spectrum of cosmic rays (cosmic ray nuclei). In the energy range between a few GeV (10⁹ eV) to about 10¹⁷ eV, there is indirect evidence for a Galactic origin of CRs based upon composition measurements with KASCADE (see e.g. [1, 2] for reviews). The knee-feature might result from a superposition of different spectra from the various nuclei, leading to heavier composition towards higher energies, consistent with measurements [3].
If the origin of cosmic rays of up to \(10^{17}\) eV is Galactic, there must be Galactic pevatrons that accelerate these particles up to the PeV regime inside our galaxy, resulting in hard gamma-ray spectra (decay of \(\pi^0\) from hadronic interactions) up to several hundreds of TeV [4]. While several detections of SNR at GeV/TeV gamma-ray energies apparently support the idea of shell-type supernova remnants being cosmic ray accelerators [5], existing data does not rule out a leptonic origin of the emission [6]. Moreover, if present, the observed spectral cut-off energies of shell-type SNR are too low by two orders of magnitude for cosmic ray pevatrons.

Searching for cosmic ray pevatrons requires observations at energies at and beyond 100 TeV gamma-ray energies. In this energy regime, a hard gamma-ray spectrum (such as expected from a pevatron) cannot be explained by inverse Compton emission (leptonic scenario), because the interaction would take place in the deep Klein-Nishina regime. Hard spectra in the UHE regime are an unambiguous signature of cosmic ray acceleration.

Accessing these energies necessitates a very large effective detector area, which is feasible using the Cherenkov technique, first proposed by [7]. The new ground-based, large-area, wide-angle, non-imaging Cherenkov air-shower experiment HiSCORE will allow measurements of cosmic rays in the energy range from 100 TeV to 1 EeV, and gamma-ray observations in the so far poorly covered ultra-high energy gamma-ray regime (UHE gamma rays, \(E > 10\) TeV). These and several other physics motivations are described in [8, 9]. In section 3, the potential of HiSCORE for gamma-ray astronomy is addressed.

2. The HiSCORE detector

HiSCORE consists of an array of light-collecting detector stations distributed over a large area (up to 100 km\(^2\)) with an inter-station spacing of 100–200 m. Each individual detector station consists of 4 photomultiplier (PMT) channels equipped with light collecting Winston cones (half opening angle 30\(^\circ\)) pointing to the zenith resulting in an effective field of view of 0.6 sr, and a total light collection area of 0.5 m\(^2\) per station. More details on the HiSCORE detector hardware are given in [10]. A full detector simulation chain is described in [8]. An event reconstruction [11, 12] was implemented based on the combination of the lateral density distribution (amplitude) and the arrival time distribution of Cherenkov photons. Differences in the shower depth and the rise time of the Cherenkov signal are exploited for particle identification. This simulation and reconstruction chain was used to study the expected detector performance. In Figure 1, the effective area after reconstruction cuts, and the angular resolution of the detector are shown. Gamma-hadron separation as described in [12] was applied.

3. Gamma-ray sensitivity and pevatron search

Necessary ingredients for the calculation of the gamma-ray point-source sensitivity of HiSCORE are the effective area, the angular resolution (see Figure 1 and Figure 2), and a parametrization of the expected hadronic background. The polygonato model [3] was used for the latter. The expected hadronic cosmic ray events were calculated using this parametrization weighted with the effective areas of the corresponding particle groups (p, light, medium, heavy). The resulting sensitivity to gamma-ray point-sources after 1000 h of observation is shown in Figure 3. Within a year, HiSCORE will cover \(\pi\) sr of the sky at an observation depth of more than 200 h per year. Thus, the sensitivity shown is valid for each point within this large field of view after 5 years of observation. Depending on the source location, the exposure can be significantly increased by tilting the detector optical axis. For example, for a northern observation site and by tilting each station by 25\(^\circ\) to the north results in more than 500 h exposure time per year for the Tycho supernova remnant. In order to estimate the capabilities of HiSCORE for specific sources, differential count rates from potential gamma-ray sources were calculated. Event lists were generated following input spectra (source and background), weighted with corresponding effective areas, efficiency-corrected for angular resolution, and energy-corrected following the
Figure 1. Effective areas for the simulated particle types after application of gamma-ray selection cuts. Proton rejection is poor, but iron suppression is substantial.

Figure 2. Angular resolution using different artificial time jitters. The time jitter reflects the accuracy of the time calibration. We aim at an accuracy of 1 ns.

simulated reconstructed energy response functions. The background was estimated as described above. The resulting expected reconstructed energy flux for the Tycho supernova remnant after 5 years of observation with a 10 km$^2$ array, and for MGRO J1908+06 are given in Figure 4. Known VHE spectra were extrapolated using powerlaw functions with an additional cutoff
factor $\exp\left(-\sqrt{E/E_C} \text{ TeV}\right)$, and including absorption by pair production of gamma rays in the interstellar radiation field and the cosmic microwave background. The value of $E_C$ was set to 300 TeV for MGRO J1908+06 and 400 TeV for Tycho.

**Figure 3.** Gamma-ray point-source survey sensitivity for HiSCORE (thick solid and dashed lines). For comparison VHE data [13, 14], and sensitivity curves from other experiments are shown. HiSCORE will extend the energy range deep into the UHE regime.

**Figure 4.** VHE data [15, 16, 17] and UHE expectations for HiSCORE from MGRO J1908+06 (black symbols) and Tycho (grey symbols), as calculated from simulations and flux extrapolations using a powerlaw with square-root exponential cutoff.
4. Status and outlook
Different detector geometries using different inter-station spacings, including variable spacings, are under study. The choice of the observatory site depends on the region of the sky to be accessed and on the desired energy range. A higher site altitude is of benefit at low energies and also has repercussions on the optimum detector geometry. A 2-channel prototype station was developed and deployed at the Tunka cosmic ray facility [18] site in Siberia. First measurements were performed using the readout system of the Tunka experiment, resulting in the detection of first Cherenkov light signals by HiSCORE (see [10]). Related activities on the Tunka site addressing air-shower observations by radio measurements are described in [19].

5. Summary
The HiSCORE air-shower detector will open up the last remaining observation window of gamma-ray astronomy, providing a deep look at the multi-TeV to PeV accelerator sky ($E > 10 \text{ TeV}$). Measurements of the spectrum and chemical composition of cosmic rays will be possible from 100 TeV to 1 EeV (with 100 km$^2$ detector area), covering the supposed transition range from a Galactic to an extragalactic origin of cosmic rays. The point-source sensitivity of HiSCORE will extend the sensitive energy range beyond the CTA energy regime. Studies of extrapolated spectra from known Galactic sources demonstrate the potential of HiSCORE for an investigation of the continuation of their spectra and a first detection of Galactic pevatrons. While absorption in Galactic low-energy radiation fields becomes important in the multi-TeV regime, this absorption will not dramatically infringe potential detections (also see [9]).

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