HERD: an innovative detector for new energy horizons in direct detection of cosmic rays

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Summary. — The HERD (*High Energy cosmic-Radiation Detection facility*) experiment is a future experiment for the direct detection of cosmic rays, that will be installed on the Chinese space station in 2027. It is based on a calorimeter with an innovative geometry: it is indeed composed of about 7500 LYSO cubic scintillating crystals assembled in a spheroidal shape. Thanks to this specific geometry and to the equipment of sub-detectors on five sides around the calorimeter, HERD will be capable to detect particles entering from five sides. This will lead to an increment in the geometric factor of more than one order of magnitude compared to the current in-orbit calorimetric experiments. Thanks to its enormous geometric factor HERD will extend cosmic-ray direct measurements more than one order of magnitude in energy. Indeed, it will directly detect for the first time the proton and helium *knee*. In addition, it will measure electron+positron flux up to tens of TeV looking for local sources of high energy leptons and for indirect signals of dark matter. Finally, HERD will also be a gamma-ray observatory. It is designed to be a new instrument for multi-messenger astronomy, study cosmic-ray acceleration sources and look for indirect signals of dark matter. In this article we will introduce the HERD experiment with its scientific objectives and its detector.

1. – Introduction

The cosmic-ray differential flux energy dependence can be described as $E^{-\gamma}$, with the spectral index $\gamma \simeq 2.7$ below PeV [1, 2]. Thus, to measure the cosmic-ray flux at high energies we need experiments with larger geometric acceptances. The direct detection of cosmic rays, the one performed in space, is indeed limited at high energy due to the limit about the mass (and on the dimension as consequence) of space experiments. Some of the most representative experiments in space for direct detection of cosmic rays are: AMS-02 [3], CALET [4] and DAMPE [5]. The first one is a magnetic spectrometer, while the others are calorimeters. They are detectors that accept particles entering only from the top side, and their effective geometric factors (the geometric acceptance multiplied for the detection efficiency) are of the order of 0.2-0.3 m^2sr. With direct experiments

up to now we have measured protons and nuclei fluxes up to about tens of TeV/nucleon, and electron+positron flux up to few TeV.
On the other hand, we have measured the cosmic-ray flux up to 10^{21} eV with indirect experiments, which measure the *Extensive Air Showers* produced by the interaction of high energy cosmic rays with the atmosphere [2, 6, 7]. However, these measurements are not accurate as the one in space, and their interpretation strongly depends on the hadronic interaction models used to simulate these events, which are affected by significative uncertainties.
Thus, for an accurate investigation of the cosmic ray flux and physics at high energy we need space experiments with larger effective geometric factors. For these reasons the HERD experiment [8, 9] has been studied and designed: a future space experiment based on an innovative calorimeter design that will be installed on the Chinese Space Station in 2027. It will have an effective geometric factor more than one order of magnitude larger compared to current in-orbit experiments and so, it will investigate directly high energy regions of the cosmic-ray flux that have been observed only by indirect experiments. In this paper we will introduce the main scientific objectives of the HERD experiment, and the design of its detector.

2. – Scientific objectives

HERD will explore energy region up to the PeV/nucleon for proton and nuclei, and up to tens of TeV for electrons+positrons. In addition, it will be a gamma-ray observatory too. We will briefly discuss the main physics targets for these three different groups of particles.

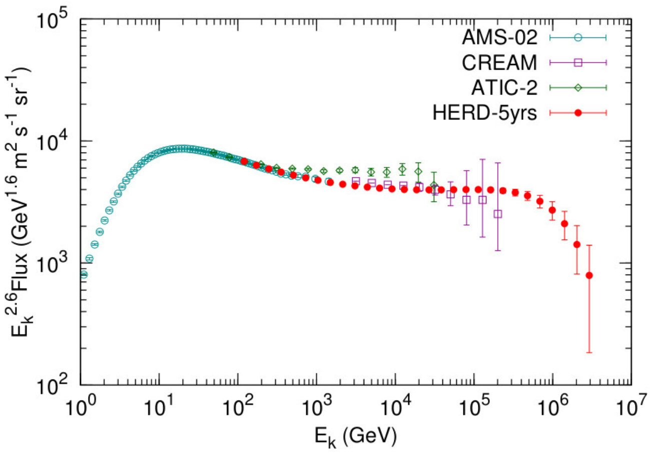

Fig. 1. – Projection of HERD five years measurement of proton flux.[9]

2˙1. *Protons and nuclei*. – For what concerns protons and nuclei HERD will measure their flux up to few PeV/nucleon. Thus, it will measure the proton and Helium cosmic-ray *knee* for the first time directly, providing invaluable information on this structure of the cosmic-ray flux where the spectral index changes from about 2.7 to about 3. In Figure 1 we show the projection of HERD 5 years measurement of proton flux: we clearly see that HERD will be capable to measure the proton *knee*.

In addition, HERD will measure nuclei fluxes up to iron and beyond, in order to investigate the cosmic-ray propagation mechanism in the galaxy and to look for possible new spectral features. Indeed, a hardening in proton and helium fluxes at about 200 $GeV/nucleon$ has been discovered by the PAMELA experiment [10], and recently a softening above 10 $TeV/nucleon$ [11] has been observed too. In addition, a hardening compatible with the ones of proton and helium has been observed for other nuclei such as oxygen and carbon [12, 13]. In such environment of discoveries HERD will provide more accurate measurements of the observed structures, and will look for possible hardening and softening in more nuclei species in order to better understand the origin of these structures.

2˙2. *Electrons and positrons*. – Regarding the electron+positron flux, HERD will extend its measurement up to tens of TeV. In this way, it will be capable to search for possible local sources of such high energetic leptons. Indeed, if these sources exist, their presence would cause a structure in the electron+positron flux that HERD will be capable to measure. For example, in Figure 2 we report a projection of two possible high energy electron+positron flux measurements of HERD considering the supernova remnant Cygnus Loop as source.

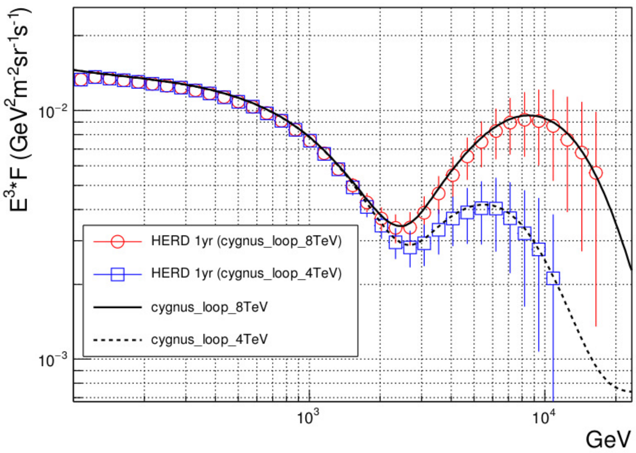

Fig. 2. – Projection of the high energy electron+positron flux measurement of HERD if the SNR Cygnus Loop can accelerate high energy electrons and positrons. Two curves are present because two different energy cut-offs in the source are considered.[9]

Moreover, HERD will look for possible indirect signals of dark matter. Indeed, we expect that if dark matter particles could decay producing high energy electrons, this would cause an unexpected structure in the high energy electron+positron flux [14].

2˙3. *Gamma-rays*. – HERD will also detect gamma-ray with two main objectives. The first one is to look for possible indirect signals of dark matter. Indeed, if the annihilation of particle-antiparticle of dark matter could produce gamma-ray couple, this would lead to a structure in the high energy gamma-ray flux. In addition, HERD will be a gamma-ray observatory for monitoring transient phenomena and giving a contribution to multi-messenger astronomy.

3. – The HERD detector

In the previous section we have briefly illustrated some of the main measurements HERD have been designed for. In this section we will briefly describe the detector and how it will be capable to extend direct measurements at such high energies. A scheme of the HERD detector is shown in Figure 3.
The heart of the experiment is an innovative calorimeter designed thanks to the CaloCube *R&D* project [15, 16]. It consists of about 7500 LYSO cubic scintillating crystals of side 3 *cm*. The crystals are assembled in a spheroidal calorimeter. Thus, the HERD calorimeter is homogeneous, 3D segmented, isotropic, deep (about 55 *radiation length* and 3 *hadronic interaction length* for particles passing near the center of the detector) and with a good energy resolution (about 2.5% for electromagnetic showers and less than 30 % for hadronic ones). Indeed, the calorimeter is able to reconstruct with the same performance particles entering from every direction. In order to take full advantage of the calorimeter characteristics, it is surrounded on five sides (all except the one connected to the space station) by multiple sub-detectors. This will enlarge the HERD effective geometric factor enormously, at the cost of only a reasonable increase in the weight and the power consumption of the payload, with respect to the current in-orbit experiments which detect particles entering only from the top side. Indeed, the HERD effective geometric factor is of about 2.5 m^2sr for electrons and about 1 m^2sr for protons: more than one order of magnitude larger than that of current in-orbit experiments.

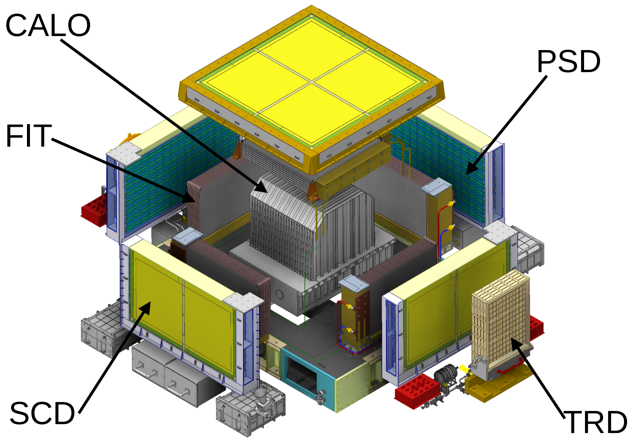

Fig. 3. – Schematic picture of the HERD detector: at the center the calorimeter (CALO), going outside the FIber Tracker (FIT), on the outermost the Plastic Scintillator Detector (PSD) and the Silicon Charge Detector (SCD). On one side we also have the Transition Radiation Detector (TRD).

3˙1. *The calorimeter*. – About the calorimeter, a very important feature is the read-out for the scintillation light of LYSO crystals [17]. Indeed, if we want to measure protons up to the PeV energy, we expect energy releases in the single crystal up to about 250 TeV, but at the same time we want also to detect *Minimum Ionizing Particle* energy deposits of about 30 MeV in order to calibrate the system. Thus, we need a read-out system with an extremely high dynamic range: larger than 10^7. The main read-out system is

based on the use of *WaveLenght Shifting Fibers* (WLSFs) coupled to *Intensified scientific CMOS* [18]. Every crystal is read-out by two different WLSFs: one connected to a high gain CMOS and the other one to a low gain CMOS. This design is necessary in order to reach the desired dynamic range.
An alternative system that could be possibly used in addition to the WLSFs is the *Double Photodiode* read-out system (PD system) [19, 20, 21]. It is based on the use of two photodiodes with different active areas (the larger sensible to smaller signals, the smaller sensible to larger signals) connected to a *Front End Electronics* that can switch in real time between high gain and low gain regime. Also in this case the use of two photodiodes with different active areas, and of an electronic that can change gain is necessary in order to reach the desired dynamic range. The use of two independent read-out systems for the calorimeter would provide a better check on the energy scale, independent triggers and redundancy.

3˙2. *The sub-detectors.* – The outermost sub-detector of HERD is the *Silicon Charge Detector* (SCD) [22], whose goal is to perform the charge measurement minimizing fragmentation of the nuclei. It is constituted by silicon strip detectors. Going inside the payload we have the *Plastic Scintillator Detector* (PSD) [23, 24], constituted by bars of plastic scintillator. Its main tasks are to provide an additional measurement of the charge and to be used as anticoincidence system. Finally, the last before reaching the calorimeter is the *Fiber Tracker* (FIT) [25], for particle tracking and detection of low energy gamma-ray. It is constituted by plastic scintillating fibers read-out by Silicon PhotoMultiplier.
Finally, there is an additional detector: the *Transition Radiation Detector* (TRD) [26, 27], based on a Thick-Gas Electron Multiplier. The TRD will be calibrated on ground with high energy electron beams for the same Lorentz γ factor corresponding to protons of 1 TeV. It will tag 1 TeV cosmic protons in space, that will be used to cross-check the calibration of the calorimeter. This innovative idea, together with the possible double read-out, will give us a strong understanding on the calorimeter energy scale.

4. – Conclusion

The HERD experiment is a future space based experiment that will be installed on the Chinese space station in 2027. It is based on an innovative calorimeter that will give the experiment an effective geometric factor of more than one order magnitude larger than that of current in-orbit experiments. Thanks to this, HERD will detect directly proton and nuclei fluxes up to PeV/nucleon energy, and electron+positron flux up to tens of TeV, in order to search for new possible spectral features and possible indirect signals of dark matter. We look forward to flying in 2027.

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