Snowmass2021 - Letter of Interest

Highest Energy Galactic Cosmic Rays

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (EF06) QCD and strong interactions:Hadronic structure and forward QCD

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Other LoI: see last page for further to this topic relevant LoI.

Abstract: Investigations of the energy spectrum, mass composition and arrival directions of cosmic rays in the energy range of PeV to EeV are important for understanding the origin of both galactic and extragalactic cosmic rays. The origin of the highest energy Galactic cosmic rays is still not understood, nor is the transition to EeV extragalactic particles. Enhancements of existing air-shower arrays as well as new installations are in progress to achieve measurements with better accuracy and higher statistics. In this Letter of Interest (LoI) the scientific motivation and current results are presented, and the foreseen experimental improvements are discussed. There remain uncertainties in aspects of the physics of air showers in the PeV to EeV energy range, so the effects of using different hadronic interaction models for interpreting air-shower data will also be addressed.

1 The Science Case

Experimental cosmic-ray (CR) research aims to determine the energy spectrum, the elemental composition and the arrival direction distribution of incoming cosmic particles. Such measurements are essential for understanding the sources, acceleration and propagation of these energetic particles of cosmic origin. At energies above 10^{14} eV, the characteristics of these particles are determined indirectly from measured properties of the extensive air showers (EAS) induced by primary cosmic rays in Earth's atmosphere[1]. The all-particle spectrum has a steep power-law like behavior with features known as 'knee' and 'ankle' at 2-5 $\cdot$ 10^{15} eV and 2-8 $\cdot$ 10^{18} eV, respectively. Whereas at the knee the spectrum steepens, the ankle is characterized by a flattening of the spectrum. Cosmic rays below the knee are of galactic origin and cosmic rays above the ankle are most probably of extragalactic origin[2,3]. Somewhere in the energy range from 10^{16} eV to a few 10^{18} eV the transition of cosmic rays from galactic to extragalactic origin is expected. There are, however, still major issues regarding the highest energy Galactic Cosmic Rays (GCR)[4]:

- The most powerful accelerators of cosmic rays in our Milky Way have not yet been revealed.
- The maximum energies of various possible acceleration mechanisms and sources are uncertain.
- The Galactic-extragalactic transition and several features in the CR energy spectrum, such as the knee or the ankle to name the most prominent, are not well understood.

These questions can be addressed through improved measurements of GCR in conjunction with gamma-ray and neutrino observations. That means that we must bring multi-messenger astrophysics to maturity not only at the ultra-high energy range, but also in the galactic scenario at lower energies. In this LoI, we outline the opportunities for research regarding the high-energy GCR in order to answer the most urgent scientific questions:

- We need to determine the maximum acceleration energy for GCR and understand the transition from Galactic to extragalactic cosmic rays. This may be accomplished by discovering the most energetic source in the Milky Way, where the Galactic Center is a promising candidate[5,6].
- We need to clarify the nature of all features in the energy spectrum. Are they related to different populations of sources or magnetic diffusion of the CRs during propagation? How are features in the energy spectrum linked to observed features in the large-scale anisotropy?
- We have to describe the full picture of sources and propagation of GCR using joint interpretations with other astrophysical messengers, such as PeV neutrinos and photons while including information on galactic magnetic fields.
- We need to resolve apparent differences between CR measurements by various air-shower arrays[7]. To what extent are they of cosmic origin and to what extent to the uncertainty of the hadronic interaction models required for the air shower interpretation?
- We must use GCR to access particle physics beyond the phase space of current human-made accelerators. A better understanding of hadronic interactions is an important science goal by itself, and it is also required to fix the mismatch in muons between simulations and data[8–12], which constitutes a major systematic uncertainty for the interpretation of GCR measurements[13]. In addition, a better understanding of the air showers is also important for the neutrino experiments.

2 Recent Progress

GCR have a strongly mixed composition of elements from proton to iron at all energies (see[1,14–18] for reviews). Weak anisotropies have been measured for the all-particle flux[19–22], but they are difficult to interpret because the present accuracy in the measurements of air-shower arrays does not allow for efficient per-event classification of the mass of the primary particles. Theoretical models and observations suggest that GCR are predominantly accelerated by supernova shock fronts, but it is difficult to explain the origin of the most energetic GCR with this mechanism[23]. The Galactic Center might be a more powerful accelerator than supernovae, as gamma-ray observations suggest a maximum energy of at least 1 PeV for protons[5,6]. Typically it is assumed that any acceleration will provide a maximum energy for nuclei of Z times the maximum for protons, where Z is the charge number of the CR nucleus. Measuring the spectra of individual masses will resolve these so-called Peters cycles[24] of the Z dependence of the maximum acceleration energy, and will indicate how many source populations exist. These results were obtained in last years by a handful of experiments only: KASCADE-Grande[25]; IceCube/IceTop[26]; Tunka[27,28]; The Telescope Array[29]; Pierre Auger Observatory[30]; HAWC[31]. However, measurement of CRs at energies of PeV and beyond with sufficient statistics can be achieved only by indirect measurements by air showers. This remains challenging because of large uncertainties involved in this detection technique. The interpretation of the air showers to deduce the properties of the primary particle is subject to systematic uncertainties arising from different instrumentations at the various experiments and from theoretical modelling of hadronic interaction models[8]. Improving the models requires input by accelerator experiments and by enhanced air-shower arrays providing hybrid measurements of all accessible shower components.

In summary, we do not yet know what accelerates the most energetic GCR, and we need to understand the transition to extragalactic CRs. In addition to multi-messenger observations, the key for progress is to increase the measurement accuracy for GCR by enhancing detectors for air showers and by combining the information from various experiments in a multi-experimental approach.

3 Experimental Plans for the Next Decade

Multi-messenger astroparticle physics requires a solid foundation in accurate instrumentation for all cosmic messengers. While major investments in detectors for high-energy photons and neutrinos are foreseen, the required increase in accuracy for GCR can be obtained for a comparably low cost. This improvement is possible by upgrading existing air-shower detectors, where the scientific questions will be targeted with dedicated efforts for increasing the accuracy in the relevant energy range.

IceCube with its surface array IceTop covers the complete range of high-energy GCR from below 1 PeV to beyond 1 EeV[32]. The simultaneous measurement of low-energy particles at the surface and high-energy muons in the ice offers unique opportunities for the study of hadronic interactions[12], and the search for PeV photons[33]. A planned enhancement by a scintillator-radio hybrid array will significantly increase the accuracy and sky coverage of IceTop[34]. Air-Cherenkov detectors can further enhance its accuracy around a few PeV and below[35]. Finally, the planned expansion to IceCube-Gen2 will increase the exposure by an order of magnitude[36]. For studying the Galactic-to-extragalactic transition range, the most important contributions in the next years are expected from the low-energy extensions of the two leading observatories for ultra-high-energy CRs: the Pierre Auger Observatory[30] and the Telescope Array[29]. The TALE fluorescence detector at TA covers the energy range from about 2 PeV to beyond 1 EeV in monocular mode[29], and the range above 100 PeV in a recently enabled hybrid mode with scintillation detectors[37]. To reach energies below 1 PeV, another planned addition to TALE is the Non-Imaging Cherenkov Array (NICHE)[38]. The Auger enhancements that reach below 100 PeV consist of underground muon detectors[39], complementing the upgrade of the surface array[40], the fluorescence[30], and the radio detectors[41]. The entire data from the meanwhile dismantled KASCADE-Grande experiment is available via a public webpage, KCDC[42]. Several future observatories with different main objectives will also contribute to GCR science, e.g., HAWC[31], SWGO[43], LHAASO[44], TAIGA[45], GRAPES[46], and GRANDproto300[47].

The increase in accuracy, exposure and sky coverage provided by all these experiments will bring unprecedented sensitivity to the science questions raised in this LoI. Hence, the contribution of GCR to multi-messenger astrophysics will be lifted to a new level providing a real chance finally to discover the most energetic accelerators in our Milky Way.

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Cross-references to relevant LoIs of Snowmass 2021:

- IceCube and Cosmic Rays — David Seckel et al.
- Radio Detection of Cosmic Rays — Frank G. Schröder et al.
- Studies of the Muon Excess in Cosmic Ray Air Showers — Dennis Soldin et al.
- A next-generation cosmic-ray detector to study the physics and properties of the highest-energy particles in Nature — J.R. Hörandel et al.
- Forward Physics Facility — Jonathan Lee Feng et al.
- Cosmic Neutrino Probes of Fundamental Physics — Albrecht karle et al.
- Synergy of astro-particle physics and collider physics — Luis A. Anchordoqui et al.
- Cosmic Rays in the TeV to PeV Energy Range — Kristi L. Engel et al.