Snowmass2021 - Letter of Interest

Establishing ultra-high-energy cosmic rays as a cutting-edge courier of the multi-messenger program

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
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The origin and nature of ultra-high-energy cosmic rays (UHECRs), the most energetic particles ever observed, are fundamental questions whose answers appear to be within our reach in the coming decade. Deflections by intergalactic and Galactic magnetic fields blur and distort the distribution of their arrival directions, but imprints of their source distribution are expected to remain. The recent discovery of a 6.5% dipole moment at energies above 8×10^{18} eV demonstrates that accumulating statistics is indispensable to detect subtle manifestations of UHECR sources in the sky. Evidence has been accumulating for intermediate-scale anisotropies at energies above around 4×10^{19} eV, some in regions of the sky close to known extragalactic gamma-ray emitters. The Pierre Auger Observatory and Telescope Array are currently being upgraded in order to take data respectively with better composition sensitivity and more effective area than today, confirm or refute the evidence for anisotropies, and hopefully identify some classes of objects as UHECR sources. This will provide valuable information about particle physics in extreme environments far out of the reach of Earth-based accelerators, complementary to what we get from astrophysical gamma rays, neutrinos and gravitational waves, making charged cosmic rays the fourth "courier" in multi-messenger high-energy astrophysics.

Perspectives for the next decade: Ultra-high-energy cosmic rays (UHECRs) are particles (mainly protons and other nuclei) with energies $E \geq 1\ \mathrm{EeV} = 10^{18}\ \mathrm{eV} \approx 0.16\ \mathrm{J}$, about which there are many open questions which will be answered in the coming years, opening up a new branch of astronomy and astrophysics: *What is the nature and origin of UHECRs? How are UHECRs accelerated to such extreme energies? Are there multiple types of sources and acceleration mechanisms? How does the nuclear composition of UHECRs evolve as a function of energy?* In order to address these questions, the goals for the next decade will be: to identify one or more nearby UHECR sources; to refine the spectrum and composition of the highest-energy Galactic and extragalactic cosmic rays; and to develop novel techniques for analyzing the distribution of UHECR arrival directions to make charged-particle astronomy a reality. This agenda is largely achievable in the next decade, thanks to major experimental upgrades underway.

State-of-the-art: The largest operating UHECR detector arrays are the Pierre Auger Observatory (hereinafter Auger) in Argentina[1] and the Telescope Array (TA) in the US[2], each detecting several thousand UHECR events per year. They cover the entire southern and northern celestial hemisphere, respectively, plus a band around the equator ($-15.7^\circ < \delta < +44.8^\circ$) where their fields of view overlap. In spite of all these data, nearly 60 years after the discovery of UHECRs[3] their sources are still unknown, and the mechanism by which they achieve such energies remains one of the main open questions in astroparticle physics. Various hypotheses have been put forward (see e.g. Refs.[4,5] and references therein), mostly involving diffusive shock acceleration in extreme astrophysical environments. Unlike neutral particles, UHECRs can be deflected by intergalactic and Galactic magnetic fields, so their arrival directions do not directly correspond to the position of their sources, preventing straightforward "cosmic-ray astronomy" analogous to photon, neutrino, and gravitational-wave astronomy. On the other hand, the distribution of their arrival directions does retain some information about the distribution of their sources, which can be retrieved using enough statistics.

Assuredly, the most recent big news concerning the origin of UHECRs has been the discovery[6] of a large-scale hemispherical asymmetry in the arrival direction distribution of events recorded by Auger. At energies starting from $8\ \mathrm{EeV}$, the data exhibit a modulation corresponding (assuming zero higher multipoles) to a dipole with an amplitude $d = 6.5\%$ pointing to Galactic coordinates $(l, b) = (233^\circ, -13^\circ)$, which is 125° away from the Galactic Center. This indicates a dominantly extragalactic origin for UHECRs: a Galactic origin would result in a much stronger dipole $d \gtrsim 80\%$, in a direction within a few tens of degrees of the Galactic Center. The direction of the observed UHECR dipole is about 55° away from that of the dipole in the 2MRS galaxy distribution[7], a deviation within the range of expectations for deflections by Galactic magnetic fields. Splitting this energy bin into three (8–16 EeV, 16–32 EeV and 32 EeV–∞) and adding a bin from $4\ \mathrm{EeV}$ to $8\ \mathrm{EeV}$ (in which $d = 2.5\%$, but compatible with isotropy within statistical uncertainties) shows that the dipole amplitude increases with energy, $d = 5.5\% \times (E/10\ \mathrm{EeV})^{0.79}$, though due to the decreasing number of events the statistical significance is actually lower in higher-energy bins[8]. This growth is compatible with expectations from propagation simulations assuming a mixed mass composition[9]. The estimated quadrupolar components of the anisotropy are not statistically significant in any of the energy bins. The statistic significance with which this modulation is detected has now reached 6σ[10]. Recent TA results[11] are compatible within their statistical uncertainites with either the Auger results or isotropy.

At higher energies, Galactic and extragalactic deflections of UHECR are expected to be small enough for point sources to be visible as warm/hot spots, for which evidence is accumulating. Auger has reported evidence[12,13] that the arrival directions of events with $E \gtrsim 40\ \mathrm{EeV}$ correlate with several classes of known extragalactic gamma-ray emitters, with 4.5σ post-trial statistical significance for starburst galaxies against the isotropic null hypothesis and 3.7σ or less for each other class of candidate sources. A test of the best-fit starburst galaxy hypothesis using TA data[14], also covering the north polar cap outside the Auger field of view, showed that the available statistics was still insufficient to exclude either isotropy or the Auger best-fit hypothesis. On the other hand, TA has reported various other indications of anisotropies, for example a 28°-

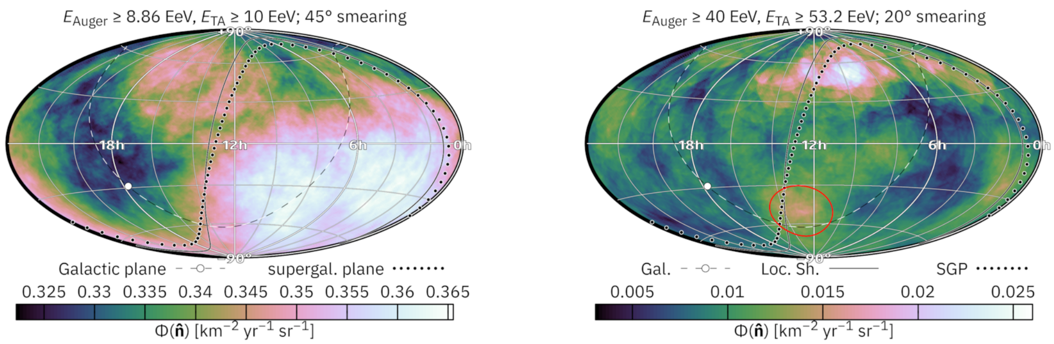

Figure 1: UHECR flux distributions observed by Auger and TA, in equatorial coordinates, from Ref.[22]

radius region of the sky with a deficit of events with $16\ \mathrm{EeV} \lesssim E \lesssim 56\ \mathrm{EeV}$ and an excess with $E \gtrsim 56\ \mathrm{EeV}$ (with 3.7σ post-trial significance)[15], and an energy-dependent pattern consistent with UHECRs originating in sources concentrated along the supergalactic plane and being deflected away from it by magnetic fields (with 4.1σ post-trial significance)[16]. Most importantly, the statistical significance of indications of medium-scale anisotropies has been increasing steadily with time. Within this decade, we expect to roughly double the size of the combined Auger-TA data sample allowing for independent discovery tests of UHECR sources.

Joint efforts are underway to search the UHECR arrival direction distribution in the whole sky for anisotropies by combining data from Auger and TA, with the energy scales matched to each other using the flux in the common declination band[17–22]. The most recent estimates of the full-sky flux distributions above two different energy thresholds are shown in Figure 1. The flux pattern visible in the left panel of Figure 1 does not look purely dipolar: a large brightest region is clearly visible in the south-east, but there also seems to be a second relatively bright region in the north-west. This may be interpreted as an indication for a possible quadrupole moment, which we will be able to confirm or refute with more statistics. The tantalizing visual correlation of high-significance regions with the supergalactic plane in the right panel of Figure 1 is currently under study. The advantage of full-sky searches is that the largest-scale anisotropies, namely the dipole and quadrupole moments, which are relatively unaffected by magnetic fields[23,24], can be estimated without making any assumptions about the strength of smaller-scale anisotropies, unlike with partial sky coverage.

The path to new discoveries: Auger and TA are currently being upgraded with hundreds of new scintillation detectors. AugerPrime[25,26] will allow us to better separate the electromagnetic and muonic components of air showers, thereby reducing the systematic uncertainties of the measurements, while enhancing the sensitivity to UHECR nuclear composition. This will in turn allow us to compose data samples enriched in light elements, for which anisotropies are expected to be stronger. TA×4[27] will allow us to detect events in the northern hemisphere, where some of the most interesting indications of anisotropies have been reported, with several times the currently available statistics. The discovery of the large-scale dipole asymmetry represents a compelling example of the power of accumulating more statistics. If the medium-scale anisotropies for which evidence has been reported are real, the upgraded detectors are expected to be able to confirm them with 5σ significance by the mid-2020s[28]. Conclusively identifying one class of objects as being UHECR sources would be a vital clue in answering the question of their acceleration mechanism, providing us with valuable information about particle physics in extreme environments.

In the new era of multi-messenger astronomy, improved measurements of the highest-energy particles will provide a compelling and complementary view of the extreme universe to that of neutrinos, gamma rays, and gravitational waves. The UHECR community is fervently responding to the new questions posed by the UHECR puzzle. The next decade will test the evidence for source candidates and build the next-generation experiments[29–31] that will usher in a new era of charged-particle astronomy.

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