Identifying the UHECR accelerators using gamma-rays

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The origin of the most energetic particles observed in nature, the ultra-high-energy cosmic-rays (UHECRs), is one of the most important open questions in astrophysics. The Pierre Auger Observatory, built to study these particles, has recently been used to make two breakthroughs in this field. Firstly, the detection of a significant *anisotropy* in the arrival directions of cosmic rays with energies above $\sim 6\times 10^{19}$ eV, and evidence for a correlation with the locations of active galactic nuclei (AGN) in the nearby universe (distance < 75 Mpc). Secondly, the measurement of a *suppression* of the cosmic ray flux at energies larger than 4×10^{19} eV. Taken together these measurements strongly suggest that the UHECRs are a) extragalactic in origin, b) have a light mass spectrum, dominated by protons. However, it is not possible at the current time to identify any individual object (or even class of objects) as an UHECR accelerator. The angular resolution of Auger ($\sim 1°$), the expected deflections in the galactic and extragalactic fields ($\geq 2°$), and the small statistics (27 events) make a solid identification using UHECRs alone very unlikely for current instruments. Perhaps the most promising avenue through which to establish an individual astrophysical object as an UHECR source is the detection of characteristic emission in the high or very-high energy γ*-ray* domain. Many predictions exist for GeV-TeV γ-ray emission, arising both from the propagation of UHECRs from their sources to the Earth, and inside the accelerator sites themselves. Fortunately, the experimental situation in γ-ray astronomy has dramatically improved in recent years. A sensitive TeV detector, HESS, is operating in the southern hemisphere, with sky coverage well matched to that of Auger. Additionally, instruments in the northern hemisphere VERITAS and MAGIC provide γ-ray coverage above declination $-10°$, corresponding to $\sim 50\%$ of the Auger sky coverage. GLAST, a wide field of view GeV γ-ray satellite mission, will be launched on the 16^{th} May. We therefore consider a systematic study of what can be learnt about the UHECR using γ-rays to be both timely and important. We propose to assemble a team of experts, combining knowledge of γ-ray and UHECR measurements with theoretical modelling of UHECR acceleration and propagation, to study and systematically reassess the complex and inter-related possibilities for γ-ray production and the detectability of the UHECR signals. The output of the work of this team will take the form of recommendations for the observation strategies of γ-ray instruments, as well as review papers addressing what can be done with the results of such observations.

1 The Ultra High Energy Cosmic Rays

The origin of the cosmic radiation has been a mystery since its discovery in 1912 by Victor Hess. The cosmic ray spectrum observed near the Earth extends over an extraordinarily wide energy range, from below 10^8 eV up to $\sim 10^{20}$ eV. The spectrum is remarkably featureless, initially it is a power law $\propto E^{-2.7}$ steepening slightly to E^{-3} at the $knee$ for energies above 10^{15} eV and exhibiting small changes in the spectral index (the $second\ knee$ and $ankle$) in the energy range 10^{18}-10^{19} eV.
The general consensus is that particles with energies below the $knee$ are accelerated inside of our galaxy and effectively confined by galactic magnetic fields. At the highest energies ($> 10^{18}$ eV) the gyro radii of protons and nuclei become so large that this containment is no longer effective. Furthermore, for such high

energies few viable acceleration sites exist inside our galaxy. For these reasons it is generally supposed that the highest energy cosmic rays are extragalactic in origin. In such scenarios, a rigidity dependent cutoff in the individual cosmic ray spectrum is expected, leading to a cosmic ray beam dominated by heavy nuclei close to the transition between the galactic and extragalactic components. Indeed, evidence for such a rigidity dependent cutoff has been found by the KASCADE collaboration [1].

Away from the intrinsic cut-off regime it is plausible that the composition of the UHECRs *at their sources* will be close to that of typical interstellar material - i.e. dominated by protons. Naturally, the fraction of protons will be enhanced by interactions of nuclei during propagation in the extragalactic medium, or within the sources, at energies above 10^{19} eV [2, 3]. Moreover, the Pierre Auger and Hi-Res Collaborations have recently (and independently) reported a suppression of the cosmic ray flux at energies larger than 4×10^{19} eV when compared to an extrapolation of the spectrum measured at lower energies [4, 5]. This flux suppression, together with the bounds on the photon fraction of the cosmic ray beam [6], has severely constrained most of the exotic *top-down* models proposed in the past to explain the UHECRs.

Therefore, the scenario that is emerging appears to be one of acceleration in extragalactic astrophysical sources and a high proton fraction in the cosmic ray beam. In such a case, the expected anisotropy of the UHECR sky is determined by three factors:

- Due to the interaction of these particles with extragalactic background photon fields (the Greisen-Zatsepin-Kuzmin or GZK effect [7]) the flux is dominated by increasingly nearby sources as we increase the energy threshold examined (for uniform sources, 90% of the protons arriving at Earth should be produced in sources located within 90 (200) Mpc for an energies above 6 (8) $\times 10^{19}$ eV) . The measurement of a flux suppression above 4×10^{19} eV provides experimental evidence for this effect.

- The distribution of baryonic matter becomes increasingly anisotropic on short distance scales, the feature known as the super-galactic plane is a main local example of this. In essentially all acceleration scenarios the UHECRs sources are expected to follow the underlying matter distribution and hence be anisotropically distributed.

- Deflections of cosmic rays in galactic and extragalactic magnetic fields will decrease at higher energies. Therefore, with increasing energy the arrival directions of the UHECR should cluster around the locations of their sources with increasing accuracy (i.e. smaller angular displacements).

The deflections expected for protons in extragalactic magnetic fields are rather uncertain, estimates vary from a few degrees to a few tens of degrees ([8, 9]). However, deflections in turbulent magnetic fields can be thought as introducing a (fairly symmetric) “Point Spread Function” on the underlying cosmic ray source distribution, and hence the arrival directions of the UHECR likely represents a smeared version of the source distribution.

Experimentally, the analysis of the distribution of arrival directions of the highest energy events collected by the Pierre Auger Observatory reported in [10] has provided evidence for a deviation from isotropy.

In that work, it has been shown that there is a significant excess of cosmic rays with energies larger than 6×10^{19} eV within $\sim 3^\circ$ of the position of AGN (given by the Veron-Cetty catalogue) located at a distance smaller than 75 Mpc from the Earth. Whether all AGN in this catalogue, or a subset of them, or other objects spatially correlated with these AGN are the sources of the highest energy cosmic rays is still a question under debate. In one year, the Pierre Auger Observatory will collect a factor of two more statistics with which it will be possible to clarify the strength of the signal reported, but, if confirmed, it will indicate that extragalactic magnetic fields are indeed not large enough to isotropise the UHECR sky, and charged particle astronomy will be a reality.

Given this situation, we are able for the first time to identify regions of the sky where it is more likely for an UHECR accelerator to be located. The purpose of this team is to explore the available astrophysical models and assess the detectability of the γ-ray emission which is expected to occur towards the directions of potential sources of UHECRs.

2 Scenarios for γ-ray Production

It is convenient to divide the expected radiation of the UHECRs into two components, that produced during propagation away from their sources, and that produced during acceleration, inside the sources themselves.

2.1 Propagation signal

The GZK suppression inevitably leads to the production of neutral pions which decay into UHE γ-rays. In addition, electron/positron pair production in $p\gamma$ interactions begins at much lower energies. The interaction of these γ-rays and electrons with the extragalactic radio to infra-red backgrounds will in general lead to the development of an electromagnetic cascade which results in much of the energy of the UHECR beam being transfered to photons of $\sim$ TeV energies. This possibility has been explored in detail by [11], [12] and [13]. Gabici & Aharonian have identified three distinct regimes for the cascade development depending on the magnetic field strength close to the source and in extragalactic space [13]. For field values of $\sim$1 nG close to the source, electromagnetic cascades are suppressed but γ-ray emission in the *GeV* range is still produced due to synchrotron emission of the secondary electrons. The detectability of such UHECR propagation signatures with TeV instruments depends critically on the angular extent of the emission, and of course on the UHECR luminosity of the sources, both of which can now be constrained using the new Auger data.

2.2 Production inside sources

As UHECRs must be accelerated in the presence of magnetic fields, radiation fields and matter, energy losses via γ-ray production are *at some level* inevitable [14]. However, the amount of energy which may be input into GeV-TeV photons varies enormously for different acceleration scenarios. Predictions for TeV emission have been made for several scenarios: for example in acceleration very close to supermassive black holes, in AGN jets and radio lobes, in galaxy clusters and in γ-ray bursts (GRBs). The correlation of UHECR arrival directions with AGN is clearly suggestive that these objects are the dominant acceleration site for the UHECRs. However, as discussed above, any source population which follows the distribution of baryonic matter in the local universe must be considered as a candidate accelerator.

In the scenario of UHECR acceleration in γ-ray bursts (GRBs) any TeV γ-ray photons emitted would arrive at the Earth long before any accompanying UHECR (due to the longer path length produced by magnetic deflections). As a consequence a one-to-one correspondence of γ-ray sources to UHECR sources is not expected. Indeed, any acceleration mechanism that occurs in bursts, rather than semi-continuously, will be very difficult to identify via γ-ray emission. A more promising alternative is acceleration associated with (extremely long lived) supermassive black holes (SMBHs) in the nuclei of galaxies. For UHE hadrons accelerated in strong magnetic fields close to SMBHs, the dominant energy loss mechanism is *curvature radiation* in the TeV energy range [15], but is only likely to escape the system for systems with low accretion rates. In active galaxies, in contrast, the acceleration site is general supposed to lie further from the SMBH - to avoid energy losses in the strong radiation fields associated with the accretion disc. UHECR acceleration in the relativistic jets in AGN and at the termination shocks of these jets at very large distances from the central engine, have both been discussed by many authors, see for example [16].

Emission from sources is clearly much less constrained by observations than the propogation signature. However, it is important to consider this channel as it may dominate in certain scenarios.

3 Experimental Situation

3.1 γ-rays

The field of γ-ray astronomy has matured significantly and has created considerable excitement in the high-energy astrophysics community in recent years through the discoveries triggered by the advance in sensitivity of atmospheric imaging Cherenkov telescopes (IACTs), represented in the new generation of instruments (H.E.S.S., MAGIC and VERITAS, which measure γ-rays above $\sim$100 GeV, see [17] for a recent review) and through wider field-of-view extensive air shower particle measuring instruments such as MILAGRO (mostly sensitive in the > 10 TeV domain). All the major IACT instruments have collaboration members represented in the proposed team. These instruments have angular resolution of better than 0.1° and *point-source* energy flux sensitivity of $\approx$2$\times$10^{-13} erg cm^{-2} s^{-1} for 50 hours of observations. The construction of the proposed CTA project would improve the sensitivity of this technique by an order of magnitude. The field of view of these instruments is 4 - 5°, reasonably well matched to the clustering scale identified by the Auger Collaboration but too small for all sky surveys to be practicable. The IACT collaborations therefore require guidance on the best use of the available observation time in the search for UHECR signals.

The experimental situation at lower photon energies will be revolutionised by the launch of the GLAST satellite,operating in the energy range above between 20 MeV and 100 GeV. A major advantage of GLAST is its wide field of view, it will see 30% of the sky at any given moment, and perform an all-sky survey very rapidly after launch. The energy flux sensitivity of GLAST is comparable to the new IACT arrays — but its angular resolution is significantly worse except at the highest energies. See [18] for a comparison of GLAST with TeV instruments. GLAST collaboration members are represented on this team.

3.2 UHECRs

The spectrum of cosmic rays above 10^{19} eV as reported by the Hi-Res and the Auger collaborations is in agreement within quoted systematic errors and shows a clear flux suppression above 4×10^{19} eV. Efforts to reduce the systematics (which are currently at the level of 20-25% in the energy scale) are ongoing and are necessary for detailed physical interpretation of the results. Below 10^{19} eV the discrepancies between Auger and HiRes are larger, the low energy extensions of the Pierre Auger Observatory and the Telescope Array experiment will hopefully clarify this situation in the near future.

The measurement of the UHECR *mass composition* and its evolution with energy are critical to constrain astrophysical models, e.g. to determine the energy at which the transition between a galactic and an extragalactic origin of the cosmic rays occurs. However, such measurements have to be interpreted in the light of the predictions of hadronic models, which are uncertain at these energies. Forthcoming accelerator experiments at 14 TeV (centre of mass) will help to break this degeneracy. The HiRes experiment and the Pierre Auger project will soon show the first results on some observables sensitive to the primary mass composition.

The 3000 km^2 southern site of the Pierre Auger Observatory is now essentially complete. The exposure of Auger in existing publications is equivalent to ~ 1 full array year, implies that the published dataset will likely double during the duration of the ISSI team (several members of Auger are represented on this team, including the spokesperson emeritus Alan Watson). To achieve significantly larger exposures, two approaches are being taken in the design of future instruments: the northern site of Auger is planned to have 3-10 times larger area but be based on the same techniques. Satellite based instrument such as JEM-EUSO, currently in phase A of a study by an international consortium led by Japan, and in the future, Super-EUSO, proposed for the Cosmic Vision Programme of ESA, will achieve even larger exposures. In the longer term it will therefore be possible to study the anisotropy of the UHECR sky in much greater detail. We believe that the activities of this team can help pave the way for the more comprehensive studies that will be possible with instruments like Auger-North and CTA.

4 Plan for Team Activities

Due to the complexity of this field, both experimentally and theoretically, and due to the huge impact of any successful detection of a TeV UHECR signature, we consider it very useful to initiate discussions between those responsible for models of TeV γ-ray production and those individuals with hands on experience of γ-ray and UHECR data analysis. To this end we propose to hold 2 one week meetings at the ISSI, with a gap of approximately 1 year. As the proposed team is very spread out geographically, the ISSI provides an ideal central location for these meetings, with the added benefit of a distraction-free environment for

all participants. We would require only internet connections and a meeting room. Financially, we would request a *per diem* for team members and travel expenses for the coordinators.
During the first of these meetings we would aim to:

- make a critical assessment of the experimental situation in UHECRs w.r.t. sources and propagation and hence anisotropy.
- produce a plan for conducting a systematic study of the phase-space for γ-ray production as a consequence of UHECR propagation - in the light of the new experimental situation in UHECRs.
- discuss the viability of the existing scenarios for γ-ray emission from the acceleration sites of UHECRs, again in the light of the new data.
- produce recommendations on observation strategy to TeV instruments and recommendations for statistical approaches to anisotropy to UHECR instrument collaborations.
- produce an initial outline for one or more journal publications

Between meetings the team will have regular conference calls to discuss progress on this topics. The second team meeting agenda will clearly depend on the progress made by the team and what new experimental findings exist. It will in any case certainly be necessary to:

- review progress in UHECR measurements and in TeV follow-up observations of UHECR clusters.
- discuss the implications of the first year of GLAST data for UHECRs.
- make an assessment of the possibilities for future instrumentation - specifically CTA, Auger North and future space-based UHECR instruments.
- Assess progress of, and make final plans for, publications arising from these team meetings.

In conclusion, we consider the activities proposed here to be both timely, due to the new Auger results, the recent improvement in the sensitivity of IACTs and the upcoming launch of the GLAST satellite, and realistic, considering the breadth of knowledge present in the proposed team.

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