RESEARCH FOCUS AND ACCOMPLISHMENTS

Current and Future Research Focus

The question which currently drives my research is **"What objects in the Universe are able to accelerate cosmic rays beyond multi-PeV energies and what are their gamma-ray signatures?"**. This question is exciting because most scenarios we can think of for accelerating particles up to PeV energies involve extreme physical environments and/or extreme exotic physics.

Cosmic ray (CR) protons and nuclei arrive at Earth with energies ranging from GeV up to the ultra relativistic energy range of 100 EeV. Clues about where their origin are derived primarily from their elemental composition and energy flux.

At energies below 100 TeV, the "Proton knee" (see left-panel of Fig. 1), the CR composition roughly matches that of our local interstellar medium. A change in their composition above the "Proton knee" is attributed to a maximum rigidity (Energy/charge) that their Galactic sources, considered to be supernova remnants (SNR), can reach [1]. CRs with energies above 100 PeV, the "Iron knee" (see left-panel of Fig. 1), are not thought containable within the Milky Way's magnetic fields, originating instead from extragalactic sources. For CRs with energies above the "Ankle" (>3 EeV), few acceleration sites are able to satisfy the Hillas criterion for their production [2]. Though this problem is alleviated somewhat if ultra high energy CRs are nuclei, their acceleration to these energies still requires remarkable astrophysical conditions.

The composition of CRs above the "Iron knee" is now probed with unprecedented statistics by the Pierre Auger Observatory (PAO). Results from this observatory indicate that the CR composition is light again at EeV energies before becoming heavier again at energies above the "Ankle" [3]. Furthermore, there is now evidence of anisotropy in the arrival direction of the highest energy CRs [4]. Such an unexpected change in the CR composition above the "Ankle", in a region which had previously been assumed to consist predominantly of protons, challenges theoretical models, placing tight constraints on the acceleration environment, source proximity and spectrum required to be output by the sources [5]. Indeed, should the composition remain heavy up to the highest energies observed by the PAO, some component of the extragalactic sources must be very local, lying within $\sim$60 Mpc from Earth [6].

The most luminous non-thermal objects within this local region are Active Galactic Nuclei (AGN)

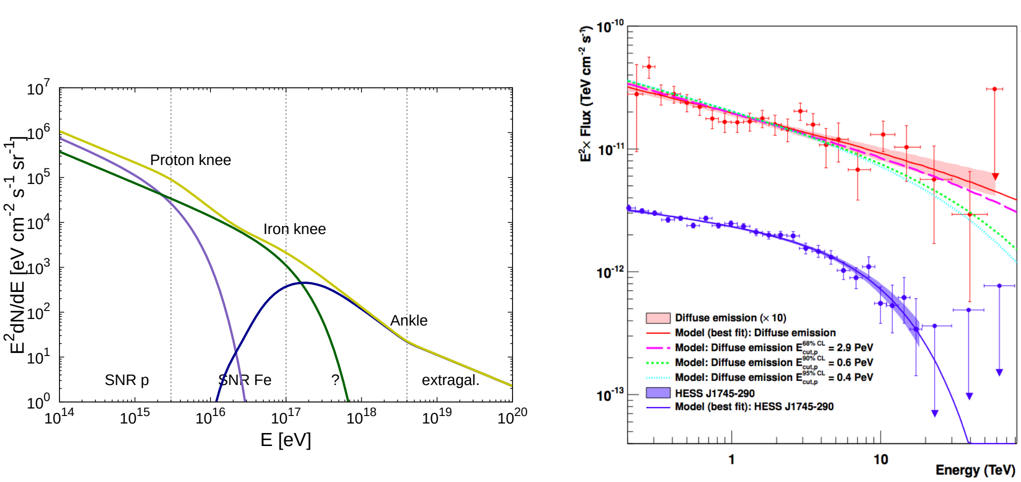

Figure 1: **Left:** Cosmic ray energy flux. **Right:** The gamma-ray energy flux (ie. spectral energy distribution) of the Galactic center PeVatron recently discovered by HESS.

with luminosities $\sim 10^{43}$ erg/s, and low luminosity GRBs (Gamma Ray Burst)[7, 8], with luminosities $\sim 10^{47}$ erg/s. Key questions which my present/near-future research aims to answer are *whether AGN and GRBs can accelerate nuclei up to energies of 100 EeV* and *whether CR nuclei from these objects can arrive with a mild anisotropic distribution in the sky consistent with the PAO results.*

New insights into the problem of the origin of CRs can be obtained through a **multi-messenger approach**. At the source, CRs interact producing secondary gamma-rays and neutrinos, which can be observed by detectors such as Fermi-LAT, HESS and IceCube. Captivatingly, observations by gamma-ray instruments, including those of HESS in which I have personally been centrally involved, have revealed high energy emission from nearby AGN/starburst galaxy systems, with the detection of both GeV and TeV gamma-rays originating from objects such as Cen A (~ 4 Mpc), M82 (~ 4 Mpc), NGC 253 (~ 4 Mpc) and M87 (~ 18 Mpc), as well as from our Galactic center region, Sgr A* [9, 10, 11, 12, 13, 14, 15].

Big efforts are presently underway to achieve GRB detections using present-day Cherenkov telescopes through extreme observations: long duration/low energy thresholds. These recent developments in multi-TeV gamma-ray astronomy are shedding fresh light on the most local potential trans-PeV CR sources. The coming decade, with the arrival of the Cherenkov Telescope Array (CTA), guarantees significant further growth in our understanding of these locally bright non-thermal sources.

Definitive signatures of the trans-PeV CR observed at Earth, however, still await to be discovered. Nevertheless, clues in this direction have been provided by the recent discovery that the Galactic center harbors a PeVatron accelerator (see right-panel of Fig. 1). Excitingly, this revelation carries big implications on both the origin of Galactic CRs, as well the potential extragalactic sources. Its achievement, however, was only possible through dedicated long-duration gamma-ray observations of the Galactic center region. This result highlights the extraordinary potential for gamma-ray observations to reveal new insights into cosmic ray origins. Although simplistic toy-model scenarios can be developed to account for the origin of this emission, thorough numerical calculations able to describe the wealth of non-thermal data connected to these observations has still to be achieved. *A focus of my coming research will be the development of Big Data tools for the analysis and numerical description of the gamma-ray emission from the Galactic center and other candidate multi-PeV sources.*

Research Accomplishments

My research has focussed on a broad range of topics in the field of cosmic ray, neutrino, gamma-ray, and AGN astrophysics. Below is a brief outline of the key areas I've worked in along with a statements summising the impact this research has had in each area.

Extragalactic Cosmic Ray Nuclei Propagation- the disintegration rates of nuclei during their propagation through extragalactic radiation fields between their sources and Earth was investigated. By incorporating photo-disintegration rates into a Monte Carlo treatment of nuclei propagation, a simulation to obtain the resultant arriving flux following a given description of the source properties was developed. My results have had direct relevance to recent Pierre Auger measurements of the extragalactic cosmic ray composition, which indicate that a non-negligible intermediate mass nuclei component exists. After confirming the stability of these results, despite the uncertainties in the photo-disintegration cross-section and the cosmic infra-red background, we developed an analytic treatment for nuclei propagation. *The analytic treatment developed provided a simple comprehensive description whose results encapsulate those from the Monte Carlo method.*

Nuclei Photo-Disintegration in Extragalactic Particle Accelerators- powerful non-thermal extragalactic sources are known to possess strong radiation fields, whose presence is detrimental to the particles being accelerated. We looked into the degree of photo-disintegration expected before cosmic ray nuclei leave the acceleration region. Using the radiation fields present in candidate source environments, we determined the relative opacities to cosmic ray protons and nuclei. Under the assumptions about the source opacity to protons, we calculated the corresponding degree of disintegration expected. *In this way it was demonstrated that GRB may be unable to accelerate nuclei above 10^{16} eV before complete nuclei disintegration occurs and that similarly AGN may be found to completely disintegrate nuclei above 10^{19} eV.*

Conversely, we found that consistency of neutrino flux calculations with observations could provide strong constraints on ultra high energy (UHE) neutrino fluxes from extragalactic cosmic ray sources. My results demonstrated that diffuse neutrino flux calculations consistent with all present observational data could be as much as two orders of magnitude below the level of predictions by others in the field.

Cosmogenic Neutrinos- during their propagation from source to Earth, extragalactic cosmic rays undergo energy losses through interactions with background photons, leading to the generation of secondary UHE electrons, photons, and neutrinos fluxes. Utilising a Monte Carlo simulation of the propagation of cosmic rays, the diffuse cosmogenic neutrino flux from the entire ensemble of sources over cosmic history was determined. However, as for the neutrino flux expected from cosmic ray sources, the consideration of the presence of nuclei in the arriving extragalactic flux places contraints on how many photon interactions can have occured on average between the source and Earth. *We showed strong constraints could be placed on the cosmogenic neutrino flux through the presence of nuclei in the arriving extragalactic cosmic ray flux at Earth.*

Ultra High Energy Gamma-Rays- we investigated the component of UHE photons generated through extragalactic cosmic ray energy loss interactions. Following their production, we calculated their subsequent interactions with background radiation fields, and the production of electron/positron pairs. With production scales of the order of 10-1000 Mpc (Mpc$\approx$3 million light years) and subsequent energy loss scales of the order 1-100 Mpc, we demonstrated that UHE photons are ideal messengers for providing information on the extragalactic cosmic ray source distribution. *We showed that the photon component in the arriving extragalactic cosmic ray flux has the potential to determine whether the cutoff observed in the arriving spectrum truely originates from photo-pion losses during propagation.*

Electromagnetic Cascades from Powerful Extragalactic Objects- pair production interactions of the TeV gamma-rays emitted by bright non-thermal extragalactic sources feed the development of electromagnetic cascades resulting in the energy injected piling up in gamma-rays at GeV energies. Focussing on the emission from TeV blazars, the expected spectral structure produced through cascade development was calculated for different strength extragalactic magnetic fields, whose filtering nature on the spectrum allows the observed spectrum to act as a probe of the extragalactic magnetic field strength. Such filtering was noted to potentially lead to hard gamma-ray spectra arriving from flaring events, which have previously been noted to be otherwise difficult to explain. These calculations were carried out for several bright blazars, demonstrating that their GeV-TeV gamma-ray emission may be explained through such a mechanism. Through these calculations, *We determined a lower limit on the extragalactic magnetic field strength.* This limit placed exciting new requirements on viable magnetic field generation processes.

Cascade constraints on the Extragalactic Cosmic Ray Source Evolution- the energy losses from cosmic rays during their propagation in extragalactic space also feeds the development of electromagnetic cascades, contributing to the diffuse gamma-ray background at GeV energies. Recent constraints on the level of this component of the background by the Fermi collaboration subsequently place constraints on the extragalactic cosmic ray source evolution. *We showed that positive source evolution with redshift scenarios are excluded by the data and that even zero evolution models are in tension with it.*

Cosmic Rays and the Milky Way Outflow- non-thermal emission from neighbouring galaxies has revealed that outflows containing a considerable cosmic ray energy budget are a rather common phenomenon. Recently, both gamma-ray and radio observations have indicated that bubbles inflated above and below the Galactic plane by outflow from our own Galaxy also exist. Through a consideration of the hydrodynamics of such an outflow, we developed a scenario in which these cosmic rays become embedded at the base of the outflow, with different origins for observed the non-thermal radiation at different Galactic latitudes. *We demonstrated that hadronic cosmic ray interactions within the outflow and beyond could give rise to a diffuse flux of high energy neutrinos at the level recently observed by IceCube.* This result has become particularly relevant following new constraints on the contributions to the observed IceCube neutrino flux from more distant sources.

Gamma-Ray Observations of Local Bright Non-Thermal Sources- as a convenor within the HESS collaboration for the part two years, I have spear-headed efforts within the group to focus on long observations of bright sources whose emission continues without a cutoff to very high energies. The recent success of these efforts resulted in the discovery of the first PeVatron, associated with the Galactic center region. *The discovery of this first PeVatron source has thrown fresh light onto the cosmic ray origin* *problem, strengthening the motivation for galactic nuclei, and presumably active ones in particular, to become the dominant extragalactic sources at ultra high energies..*

Research at UCLA

High energy astrophysics is presently undergoing rapid growth, especially in the areas of gamma-ray and neutrino astronomy. Connecting these fields to the broader astrophysical community is vital. Furthermore, with new gamma-ray instruments such HAWC and CTA coming online presently or in the near future, scientific leadership in high energy astrophysics to take advantage of these developments is strongly desired. The Department of Physics and Astronomy at UCLA, with its rich and large ensemble of experimental and theoretical groups, is already leading the field of High Energy Astrophysics in the US, and I would personally like to be part of this progress.

Groups at UCLA: High Energy Astrophysics group, Astroparticle Physics group, Experimental Elementary Particles and Nuclear Experimental Physics Theory of Elementary Particles, Astroparticle Physics and Phenomenology (TEPAPP)

The next generation of research carried out with CTA will deepen our knowledge of high energy phenomena. Following in the direction set out by HESS2, the large telescope dishes within CTA promise to revolutionise our understanding of transient events such as GRBs. However, the Big Data challenges provided by this instrument must first be overcome. Working together with researchers at UCLA, my involvement at ISDC (the Integral Science Data Center) and my familiarity with Cherenkov telescope analysis, provide the opportunity for ARI to be heavily involved in the development and implementation of software to store and analyse the transient event data. These big data tools will be crucial for the examination and comprenhension of exciting new results and discoveries in high energy astrophysics.

References

[1] A. Bell, K. Schure, B. Reville and G. Giacinti, Mon. Not. Roy. Astron. Soc. **431** (2013) 415 doi:10.1093/mnras/stt179 [arXiv:1301.7264 [astro-ph.HE]].

[2] A. M. Hillas, "*The Origin Of Ultrahigh-Energy Cosmic Rays*", Ann. Rev. Astron. Astrophys. **22**, 425 (1984).

[3] M. Unger, f. t. P. A. Collaboration, "*Analysis of Longitudinal Air Shower Profiles measured by the Pierre Auger Observatory*", arXiv:1103.5857

[4] P. Abreu *et al.* [Pierre Auger Observatory Collaboration], "*Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter*", arXiv:1009.1855

[5] **A. M. Taylor** and F. A. Aharonian, "*The Spectral Shape and Photon Fraction as Signatures of the GZK-Cutoff*", Phys. Rev. D **79** 083010 (2009), arXiv:0811.0396

[6] **A. M. Taylor**, M. Ahlers, F. A. Aharonian, "*The need for a local source of UHE CR nuclei*", arXiv:1107.2055

[7] V. Beckmann, S. Soldi, C. R. Shrader and N. Gehrels, "*Results from the first integral agn catalogue*", arXiv:0510833

[8] W. H. Baumgartner *et al.*, "*The Swift-BAT 58 Month Survey*", Bulletin of the A.&A. Soc., **41**, 675 (2010).

[9] D. Berge *et al.*, "*Fast variability of TeV gamma-rays from the radio galaxy M87*", Science **314** 1424 (2006), arXiv:0612016

[10] F. Aharonian [HESS Collaboration], "*Discovery of very high energy gamma-ray emission from Centaurus A with H.E.S.S*", arXiv:0903.1582

[11] C. M. Hui and f. t. V. collaboration, "*VERITAS observations of M87 from 2007 to present*", arXiv:0907.4792

[12] V. A. Acciari *et al.*, "*A connection between star formation activity and cosmic rays in the starburst galaxy M 82*", arXiv:0911.0873

[13] N. Karlsson and f. t. V. collaboration, "*Discovery of VHE Gamma-ray Emission from the Starburst Galaxy M82*", arXiv:0912.3807

[14] F. Acero [The HESS Collaboration], "*Detection of Gamma Rays From a Starburst Galaxy*", arXiv:0909.4651

[15] : *et al.* [HESS Collaboration], Nature **531** (2016) 476 doi:10.1038/nature17147 [arXiv:1603.07730 [astro-ph.HE]].