The CR Connection: UHE Primaries and Secondaries from UHECR Sources

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During their acceleration, both UHECR nuclei and protons may interact with the radiation field present in the accelerator region. At UHE, such interactions lead to photo-disintegration and photo-pion production respectively. Thus, a close connection exists between the disintegration rates of UHECR nuclei in the source and the secondary UHE neutrino flux producible by the source. Upon escaping the accelerator, UHECR go on to generate a secondary UHE photon flux through photo-pion interactions with the cosmic microwave background (CMB) photons, These secondary UHE photons produced (via neutral pion decay) will themselves also interact with the cosmic radio background (CRB) photons. This leads to a second connection between UHE photons and UHECR composition. We here investigate both these connections to draw conclusions on what the presence of UHECR nuclei can tell us about the UHECR composition and their sources.

Keywords: UHECR nuclei; UHE neutrinos; UHE photons; UHECR sources

Multi-Messenger Approaches to Problems

Our multi-messenger approach is here divided into two sections. In the first of these the UHECR nuclei-proton connection is investigated. A general relationship between the interaction rates of both UHECR nuclei and protons with a general radiation field is determined. This result is used to demonstrate the strong constraints that may be placed on the source opacity to the UHECR they accelerate. In the second section, the UHECR-UHE photon connection is investigated. Motivated by the extreme cases of UHECR proton and UHECR iron nuclei fits to recent Auger results,[1] the subsequent photon flux obtained for these two cases is derived. This photon fraction is used as an indirect measure of the UHECR composition. We conclude with a summary on what we can learn through these two multi-messenger approaches.

1. Why Consider UHECR Nuclei?

Recently, the Auger collaboration has released its results on the measurements of both $\langle X_{\rm max}\rangle$ and $\mathrm{RMS}(X_{\rm max})$ using almost 4000 CR events detected by the fluorescence telescopes. These results are shown in fig. 1. For comparison, the theoretical hadronic model expectations for different nuclear species are also shown. Under the assumption that these hadronic models are representative of the present uncertainty that exists in our description of UHECR atmospheric cascades, these results suggest that UHECR become significantly heavier at energies above 10^{19} eV. Interestingly, preliminary results from LHC measurements suggest that the range of hadronic models considered by the UHECR community do indeed span the present range of uncertainties in the high energy physics of UHECR cascades.[2]

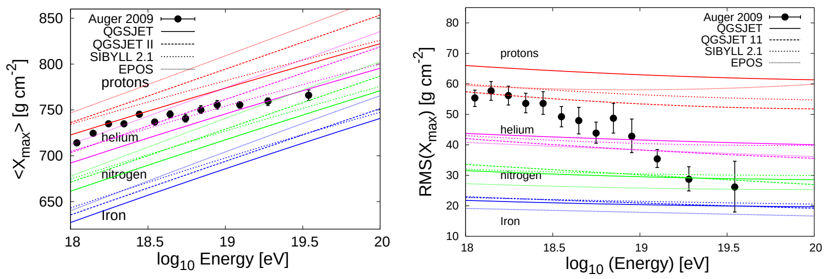

Fig. 1. **Left-Panel:** The $\langle X_{\rm max}\rangle$ distribution of arriving UHECR measured by the Auger observatory.[1] **Right-Panel:** The $\mathrm{RMS}(X_{\rm max})$ distribution of arriving UHECR measured by the Auger observatory.[1]

2. The UHECR nuclei-proton Connection

The interaction rates of UHECR with background photons follow the general expression,

$$R = \frac{1}{2\Gamma_p^2}\int_0^\infty \frac{1}{\epsilon_\gamma^2}\frac{dn_\gamma}{d\epsilon_\gamma}d\epsilon_\gamma \int_0^{2\Gamma_p\epsilon_\gamma} \epsilon'_\gamma \sigma_{p\gamma}(\epsilon'_\gamma)d\epsilon'_\gamma \qquad (1)$$

With both nuclei-photon and proton-photon interaction cross-sections possessing an initial resonance, which dominates the interaction rate integral given above in eqn 1, an approximation for the result may be found for these cases. Applying this to UHECR protons, gives interaction rates,

$$R_{p\gamma} \approx \sigma_{p\gamma} \int_{(\xi_{p\gamma}-\Delta_{p\gamma})/2\Gamma_p}^{(\xi_{p\gamma}+\Delta_{p\gamma})/2\Gamma_p} d\epsilon_\gamma \frac{dn_\gamma(\epsilon_\gamma)}{d\epsilon_\gamma}, \tag{2}$$

where Γ_p is the proton's Lorentz factor, $\sigma_{p\gamma}$ is the mean proton-photon interaction cross-section, $dn_\gamma/d\epsilon_\gamma$ is the radiation field distribution, $\xi_{p\gamma}$ is the mean energy of the cross-section's resonance, and $\Delta_{p\gamma}$ is the width of the cross-section's resonance.

Similarly, applying 1 to photo-disintegration reactions,

$$R_{Fe\gamma} \approx \sigma_{Fe\gamma} \int_{(\xi_{Fe\gamma}-\Delta_{Fe\gamma})/2\Gamma_p}^{(\xi_{Fe\gamma}+\Delta_{Fe\gamma})/2\Gamma_p} d\epsilon_\gamma \frac{dn_\gamma(\epsilon_\gamma)}{d\epsilon_\gamma}. \tag{3}$$

The delta-resonance and giant-dipole-resonances are describable by the following parameters, $\sigma_{p\gamma} \approx 0.5$ mb, $\xi_{p\gamma} \approx 310$ MeV, $\Delta_{p\gamma} \approx 100$ MeV, $\sigma_{Fe\gamma} \approx 80$ mb, $\xi_{Fe\gamma} \approx 18$ MeV and $\Delta_{Fe\gamma} \approx 5$ MeV. The incorporation of these parameters into 2 and 3, gives the ratio between photo-pion and photo-disintegration rates,

$$R_{Fe\gamma}(\Gamma_p) \approx \frac{\sigma_{Fe\gamma}}{\sigma_{p\gamma}} R_{p\gamma}(15\ \Gamma_p) = 160 R_{p\gamma}(15\ \Gamma_p)\,. \tag{4}$$

Thus, the close connection of the photo-pion and photo-disintegration rates is unavoidable, and to first order is independent of the spectral shape of the target radiation field in the source.

With the recent Auger results suggesting that nuclei are significantly present in the UHECR flux produced from the source at energies above 10^{19} eV, *fewer than 1%* of UHECR protons can be expected to interact in the source at energies above 10^{18} eV.

3. The UHECR-UHE-photon Connection

During their propagation though extragalactic space, UHECR protons lose a significant fraction of their energy through interactions with the CMB via pair creation and photo-pion production interactions. Thus an associated UHE-photon flux arises from the decay of the neutral pions, $\pi^0 \rightarrow \gamma\gamma$, created through the $p + \gamma \rightarrow p + \pi^0$ interaction channel. These high energy photons also have their propagation range limited by background radiation fields (CMB and radio background- see left panel of fig. 2). If, besides the CMB, an additional radio background contribution is also assumed,[3,4] the interaction length for 10^{19} eV photons is approximately a few Mpc (see right panel of fig. 2). Indeed, as seen in fig 2, even if the radio background component is reduced to the CMB only component, the interaction length at 10^{19} eV increases by only a factor of 2. Thus, the uncertainties in these photon fraction calculations, due to the uncertainty in the radio background component, is small and may be considered negligible.

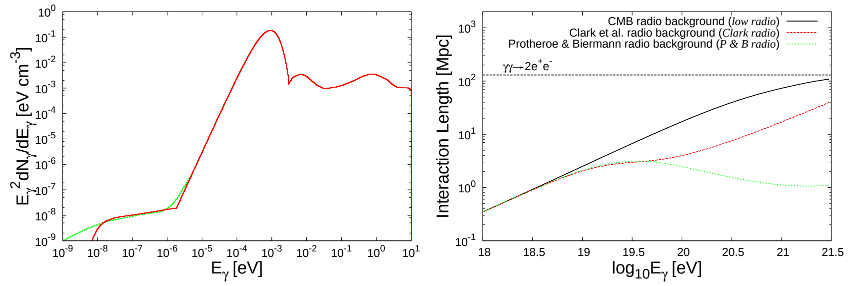

Fig. 2. **Left-Panel:** The background radiation fields impeding both UHECR proton and UHE photon propagation. The different lines in the figure represent the present uncertainty in the radio background. **Right-Panel:** The interaction rates of UHE photons in the background radiation fields. The uncertainties in the rates, due to the uncertainties in the radio background, are shown to be small at the energy of interest (10^{19} eV).

To calculate the UHECR flux at Earth, a CR source spectrum of the form $dN_{CR}/dE_{CR} \sim E_{CR}^{-\alpha} \exp(-E_{CR}/E_{\max})$ is adopted. The value of the spectral index used in this study, $\alpha = 2$, is motivated by non-relativistic first order Fermi acceleration. A best-fit value for $E_{\max}$ was found for both the "100% protons" and "100% nuclei" cases by allowing a scan over a range of $E_{\max}$ from $(Z/26) \times 10^{20}$ to $(Z/26) \times 10^{22}$ eV. The assumed spatial distribution of CR sources is $dN/dV \sim (1+z)^3$, where z is the redshift of the source. A maximum redshift of $z_{\max} = 1$ for the sources has been used for these results. Note that for the cosmologically nearby sources, to which the photon fraction is sensitive,[5] the z dependence of the cosmological source distribution is of little relevance.

In fig. 3, we show two (extreme) cases for the UHECR composition: a proton only composition and an iron nuclei only composition. As can be seen from these best fit results, a considerably larger cut-off (and subsequently a larger energy budget) is required to best-fit the data for the "100% proton" case than for the "100% iron" nuclei case. To obtain these results, a Monte Carlo simulation description of both UHECR proton and nuclei propagation have been employed, as described in.[6]

For these extreme cases, we calculate the subsequent UHE photon fluxes

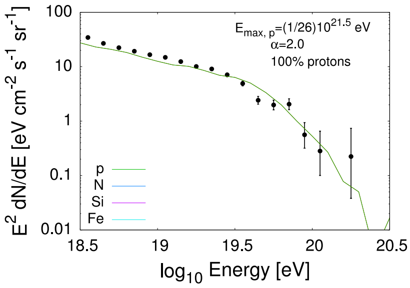

Fig. 3. **Left-Panel:** A best-fit proton only recent to recent Auger results[7] with a source injection spectrum of $\alpha = 2$ and the cut-off free to vary. **Right-Panel:** A best-fit iron only recent to recent Auger results[7] with a source injection spectrum of $\alpha = 2$ and the cut-off free to vary.

expected to contaminate these UHECR fluxes. Once again, to obtain these results, a Monte Carlo description of the UHE-photons, injected from photo-pions (π^0) produced through UHECR protons interactions with background radiation.[8] These results highlight the fact that the heavy nuclei model of UHECR can lead to a dramatic reduction in the photon fraction to levels unobservable by present UHECR detectors such as the Auger observatory.[9]

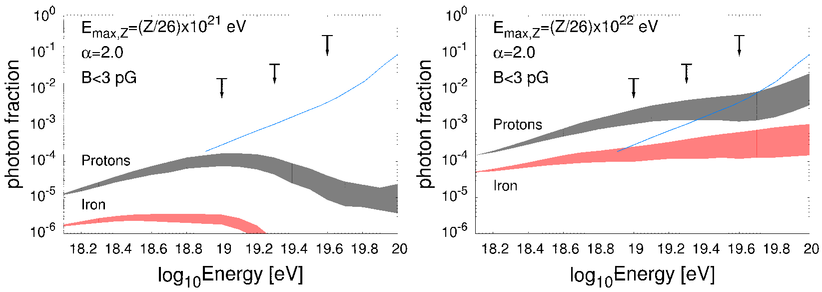

Fig. 4. **Left-Panel:** The photon fraction results obtained for a maximum energy of $E_{\max} = 10^{21}$ eV and a source spectral index of $\alpha = 2$. **Right-Panel:** The photon fraction results obtained for a maximum energy of $E_{\max} = 10^{22}$ eV and a source spectral index of $\alpha = 2$.

Conclusions

The first of our multi-messenger approaches discussed the relationship between UHECR nuclei and proton interaction rates with background radiation. Using these results, the presence of Fe in the arriving UHECR was used to demonstrate that these results demand for much smaller neutrino fluxes to be expected from these sources than obtained from calculations which ignore the strong constraints placed by the existence of UHECR nuclei. If iron nuclei are indeed being observed in the UHECR spectrum at energies above 10^{19} eV, *fewer than 1%* of UHECR protons can be interacting with the source's radiation field at energies above 10^{18} eV.

The second of our multi-messsenger approaches utilised the potential detection of the photon fraction component of UHECR spectrum. The photon fraction was demonstrated to be a powerful diagnostic tool for the UHECR composition. This followed from best-fit results for both proton and iron primary models. These fits were made to the most recent UHECR flux results[7] under the assumption that the source injection spectrum takes the form $dN/dE \propto E^{-2}e^{-E/E_{\rm max}}$. Through a comparison of these photon fraction results to predicted 20 year Auger predicted limits,[9] the predictions of these two extreme models is shown to span the present detection range. Thus, the photon fraction has some potential as a discriminator between different UHECR compositions.

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