Cosmogenic photons as a test of ultra-high energy cosmic ray composition

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Although recent measurements of the shower profiles of ultra-high energy cosmic rays suggest that they are largely initiated by heavy nuclei, such conclusions rely on hadronic interaction models which have large uncertainties. We investigate an alternative test of cosmic ray composition which is based on the observation of ultra-high energy photons produced through cosmic ray interactions with diffuse low energy photon backgrounds during intergalactic propagation. We show that if the ultra-high energy cosmic rays are dominated by heavy nuclei, the flux of these photons is suppressed by approximately an order of magnitude relative to the proton-dominated case. Future observations by the Pierre Auger Observatory may be able to use this observable to constrain the composition of the primaries, thus providing an important cross-check of hadronic interaction models.

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Despite considerable experimental and theoretical effort, the chemical composition of the ultra-high energy cosmic rays (UHECRs) remains ambiguous. Recent measurements of air shower profiles by the Pierre Auger Observatory (PAO) suggest that UHECRs are increasingly dominated by heavy nuclei at energies above $10^{18.5}$ eV [1, 2]. Uncertainties at such high energies in the hadronic interaction models used to interpret the data [3], however, can undermine this conclusion [4]. In this paper, we discuss a complementary observation that, without relying on hadronic interaction models, can be used to constrain the chemical composition of the UHECRs.

Protons with energy above $\sim 10^{19.6}$ eV (the "GZK cutoff" energy) interact efficiently with the cosmic microwave (and infrared) background, producing charged and neutral pions [5] whose decays yield potentially observable fluxes of UHE neutrinos and photons. The detection of these "cosmogenic neutrinos" [6] is a key target for present [7] and planned high energy neutrino telescopes [8]. The PAO has placed stringent limits on the fraction of UHECRs that are photons [9] and is expected to ultimately reach the level of sensitivity required to detect the cosmogenic photon flux [10].

If UHECRs are largely heavy or intermediate mass nuclei, however, they will interact with radiation backgrounds primarily through photo-disintegration, breaking up into lighter nuclei and nucleons. As these nucleons are often below the energy threshold for pion-production, fewer UHE neutrinos and photons are produced. This leads to significant suppression of the cosmogenic neutrino flux [11]. We describe here how a heavy chemical composition of the UHECR spectrum also leads to suppression of the cosmogenic photon flux. Thus as the PAO's sensitivity to UHE photons increases, this will provide a new probe of the composition of UHECRs.

Following our previous work [12], we simulate the intergalactic propagation of UHECRs by an analytically validated Monte Carlo method, including the effects of photo-pion and pair production as well as photo-disintegration (for related work see Ref. [13]). We assume that the UHECR sources are homogeneously distributed and that they produce protons or nuclei with a power-law spectrum up to a maximum energy, above which the flux is exponentially suppressed: $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha} \exp(-E/E_{\mathrm{max,Z}})$. To maintain consistency with our previous work, we express the maximum energy in terms of the quantity $E_{\mathrm{max,Z}} \equiv E_{\mathrm{max}} \times (26/Z)$, where Z is the electric charge of the cosmic ray nucleus.

If the UHECRs are all protons, a good fit to the observed cosmic ray spectrum above 10^{19} eV can be found for an injected spectrum with a spectral index in the range $\alpha \approx 1.6 - 2.4$, and $E_{\mathrm{max}} \sim (1-5) \times 10^{21}$ eV; a similar range of spectral indices can also provide reasonable fits for heavy or intermediate mass UHECRs [14]. Henceforth we set $\alpha = 2.0$, although our results depend only weakly on the precise value [15]. For iron, silicon, or nitrogen nuclei, we find that the observed spectrum requires $E_{\mathrm{max}} \gtrsim 10^{20}$, $10^{20.5}$, or 10^{21} eV, respectively. We do not consider values of E_{max} greater than 10^{22} eV since there is no plausible astrophysical source which can even contain such high energy particles [16].

Our Monte Carlo code tracks the propagation of each individual UHE nucleus, nucleon, photon, and electron down to an energy of 10^{18} eV. As they propagate, UHE photons produce e^-e^+ pairs through interactions with the cosmic radio (and microwave) background at a rate given by

$$R(E_\gamma) = \frac{2m_e^2}{E_\gamma^2} \int \frac{1}{\epsilon^2} \frac{\mathrm{d}n}{\mathrm{d}\epsilon} \mathrm{d}\epsilon \int_0^{E_\gamma \epsilon / m_e} \epsilon' \sigma_{\gamma\gamma}(E_\gamma, \epsilon') \mathrm{d}\epsilon', \quad (1)$$

where E_γ is the energy of the propagating photon, ϵ is the energy of the background photon, $\mathrm{d}n/\mathrm{d}\epsilon$ describes the background photon distribution, and $\sigma_{\gamma\gamma}(E_\gamma, \epsilon)$ is the cross-section for pair production. At energies above 10^{18} eV, the interaction length of a photon is comparable to or shorter than that of UHE protons and nuclei, *viz.* $\sim 1 - 10$ Mpc.

In each collision, the incoming photon transfers a significant fraction of its energy to an outgoing electron or positron (a plot showing this quantity for different center-of-mass energies is shown in, *e.g.*, Ref. [17]). For a 10^{19} eV (10^{20} eV) photon scattering off of a 10^{-6} eV radio photon, for example, more than 90% (97%) of the energy is transferred to the highly boosted outgoing e^-/e^+.

UHE electrons and positrons produced in this manner can subsequently regenerate an UHE photon through inverse Compton scattering with CMB photons at a rate given by

$$R(E_e) = \frac{2m_e^2}{E_e^2} \int \frac{1}{\epsilon^2} \frac{\mathrm{d}n}{\mathrm{d}\epsilon} \mathrm{d}\epsilon \int_0^{4E_e\epsilon/m_e} \epsilon' \sigma_{e\gamma}(E_e, \epsilon') \mathrm{d}\epsilon'. \quad (2)$$

Each collision transfers the bulk of the initial particle energy into the photon. We follow the development of the resulting electromagnetic cascade following the technique described in Ref. [18] (see also Ref. [19]).

Electrons and positrons can also lose energy through synchrotron radiation in magnetic fields. Whether typical UHE electrons lose a substantial fraction of their energy before inverse Compton scattering depends on the relative energy densities of the extragalactic magnetic field and the cosmic radio background. Competing with this effect is the fact that UHE nuclei and protons will also be deflected by magnetic fields, increasing their energy losses during propagation. Taken together, we find that the presence of nano-Gauss scale extragalactic magnetic fields increases slightly the resulting fraction of UHECRs that are photons at energies $\sim 10^{18}$ eV, and decreases the photon fraction at energies $> 10^{19}$ eV.

For the cosmic radio background we adopt the two extreme possibilities. The first is the estimate from observations given in Ref. [20] which may well be contaminated by foreground synchrotron emission from cosmic ray electrons in the galactic halo; hence, following Ref. [21], we consider this to represent an upper limit. We also present results for the case in which only the radio component of the cosmic microwave background contributes, representing a lower limit. We consider two specific extragalactic magnetic field strengths, ranging from the observational upper limit of $\sim 10^{-9}$ G to (negligibly) weak values of 3×10^{-12} G [18]. These field strengths bound the range of possible effects that extragalactic magnetic fields may have on the results.

We show in Fig. 1 the photon fraction of UHECRs at Earth in different models of the primary composition for the case of weak extragalactic magnetic fields (< 3 pG). If the primaries are largely protons, then the UHE photon fraction at 10^{19} eV ranges from $\sim 10^{-4}$ for $E_{\rm max} = 10^{21}$ eV to $\sim 10^{-3}$ for $E_{\rm max} = 10^{22}$ eV. The bands shown in the figure represent the variation resulting from the range of radio backgrounds considered. For comparison, we show the upper limits on the photon fraction set by the PAO [9] as well as its projected reach (after 20 years of observation) [10]. We see that proton dominated UHECR will likely provide a detectable photon fraction so long as $E_{\rm max}$ is not too close to the GZK cutoff.

The situation is very different if the UHECRs are mostly heavy or intermediate mass nuclei. Generally speaking, this leads to approximately an order of magnitude suppression of the photon fraction. If, for example, the UHECR sources inject only iron nuclei (as shown in the lower frames of Fig. 1), the photon fraction never exceeds $\sim 3 \times 10^{-4}$, and is thus beyond the reach of the PAO. For intermediate mass nuclei at source, the photon fraction is less suppressed, but is still considerably lower than for the all-proton case. Note that all of the models considered here are consistent with the cascade limit on the GeV-TeV photon flux and with bounds on the cosmogenic neutrino flux [22].

In Fig. 2, we show the photon fraction of UHECRs at Earth in different models of the primary composition for the case of 0.3 nG extragalactic magnetic fields. The effect of the presence of such a strong extragalactic magnetic field is to increase the photon fraction at energies near $\sim 10^{18}$ eV, and decrease it above 10^{19} eV, as was previously suggested in Ref. [18].

We note that our results differ somewhat from those previously presented in Ref. [23]. Whereas we find approximate agreement with Ref. [23] for the cases of protons or iron nuclei, we disagree in the case of helium. In particular, we obtain a photon fraction in the case of helium nuclei that is between the values found in the proton and iron cases, whereas Ref. [23] quotes values below those found for iron nuclei. This is puzzling as the photon fraction should predominantly depend upon the fraction of fragmented protons produced locally (*i.e.* within ~ 100 Mpc) with energies above the threshold for pion production. Since a rigidity-dependent cutoff leads to a maximum fragmented proton energy proportional to Z/A, the photon fraction for heavier nuclei should decrease monotonically with increasing A. Furthermore, pair production losses further reduce the contribution from heavy nuclei relative to lighter nuclei, and should thus decrease the photon fraction below that for lighter nuclei. It appears that although the authors of Ref. [23] did consider photopion production by secondary nucleons, they neglected pair production by protons and nuclei and photopion production by secondary nuclei [24].

Summary: We find that if ultra-high cosmic rays consist largely of heavy or intermediate mass nuclei, then the cosmogenic photon flux will be suppressed by about a factor of 10 relative to that expected for proton primaries. This provides a means of potentially discriminating between composition scenarios that is not subject to the uncertainties associated with hadronic interaction models. As the Pierre Auger Observatory continues to collect data, it is projected to reach the sensitivity required to use this distinction to constrain the chemical composition of the UHECRs. This would be complementary to the information potentially provided by future measurements of the cosmogenic neutrino flux which depends significantly on the cosmological evolution of UHECR sources – greater or fewer sources at high redshifts would lead to a higher or lower neutrino flux, respectively [22]. In con-

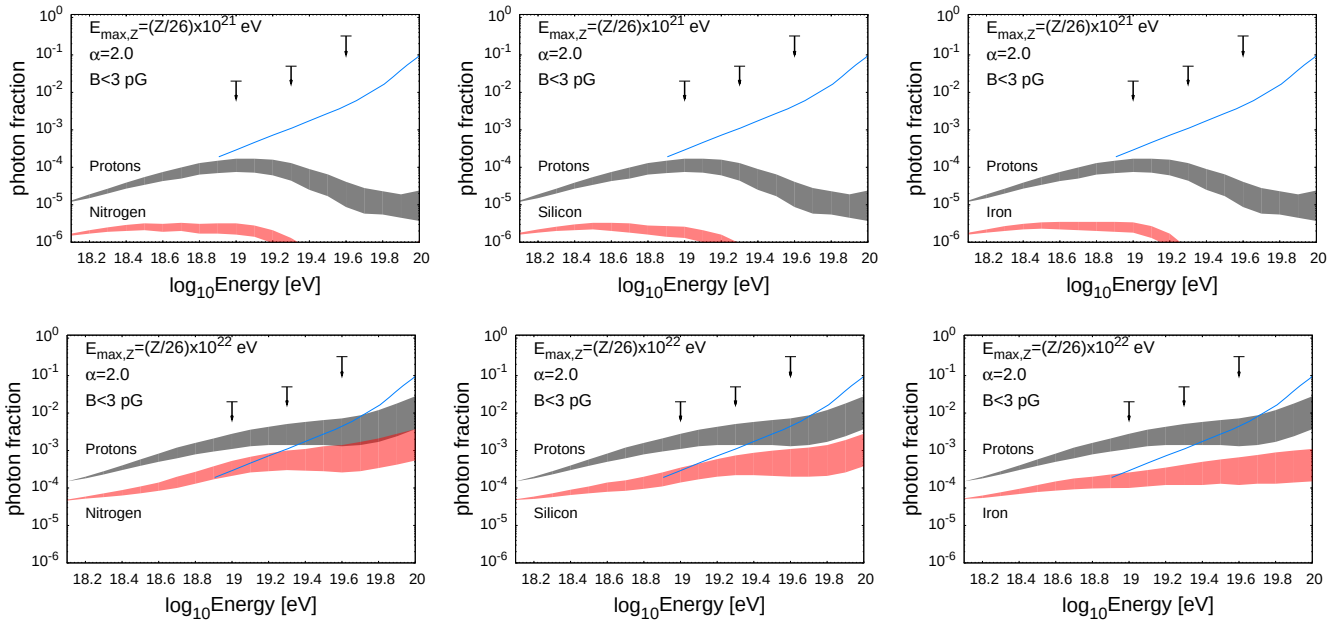

FIG. 1: The fraction of ultra-high energy cosmic rays that are photons as a function of energy for the case of weak extragalactic magnetic fields ($< 3 \times 10^{-12}$ G). Results are shown for two choices of the maximum injected energy and for models in which the cosmic ray sources inject uniquely protons, nitrogen, silicon, or iron nuclei. The bands reflect the range of the extragalactic radio backgrounds considered. Also shown are the upper limits on the photon fraction from the Pierre Auger Observatory [9] and its ultimate projected reach (blue line) [10].

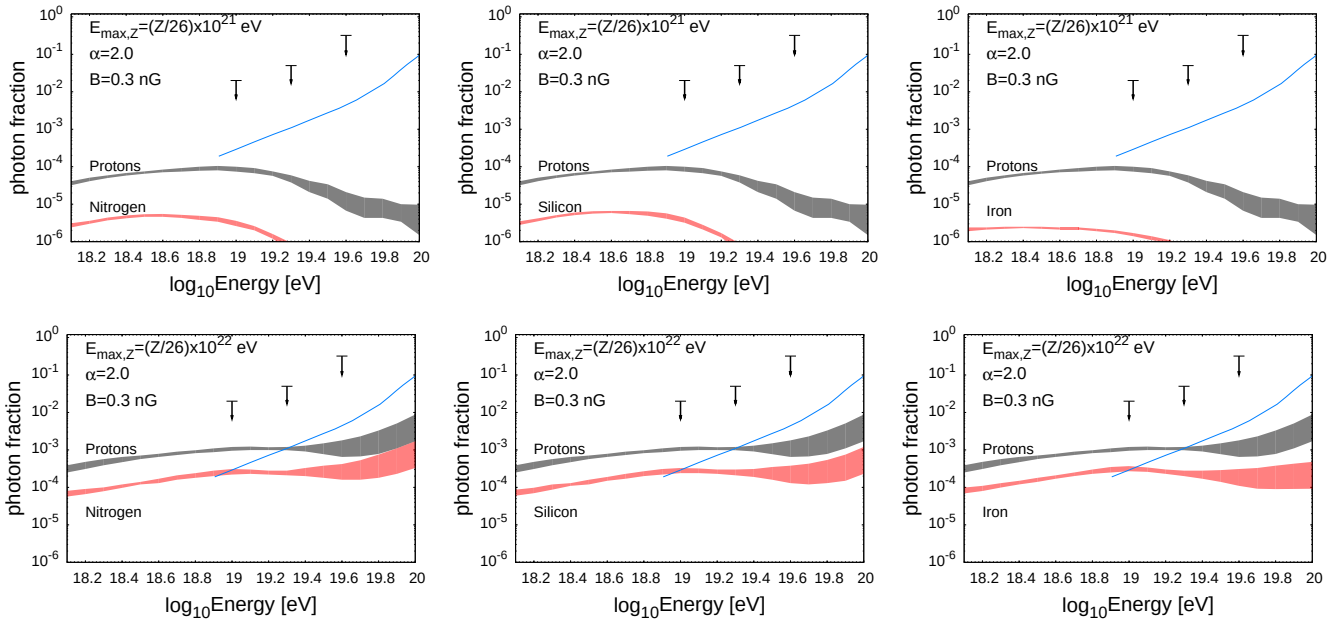

FIG. 2: The same as in Fig. 1, but for the case of 0.3 nG extragalactic magnetic fields.

trast, since any observed ultra-high energy photons must have originated within ∼100 Mpc, cosmological source evolution cannot affect their flux.

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