Violation of the Greisen-Zatsepin-Kuzmin cutoff: A tempest in a (magnetic) teapot?

Why cosmic ray energies above $10^{20}$ eV may not require new physics

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Abstract

The apparent lack of suitable astrophysical sources for the observed highest energy cosmic rays (UHECRs) within $\approx 20$ Mpc is the "GZK Paradox". We constrain representative models of the extra-galactic magnetic field structure by Faraday Rotation measurements; limits are at the $\mu$G level rather than the nG level usually assumed. In such fields, even the highest energy cosmic rays experience large deflections. This allows nearby AGNs (possibly quiet today) or GRBs to be the source of ultra-high energy cosmic rays without contradicting the GZK distance limit.

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In 1966, Greisen, Zatsepin and Kuzmin (GZK) pointed out that high enough energy protons degrade in energy over cosmologically small distances due to photopion production from the cosmic microwave background. Less than 20% of protons survive with an energy above $3 \times 10^{20}$ ($1 \times 10^{20}$) eV for a distance of 18 (60) Mpc \[2\]. Ultra-high energy (UHE) nuclei and photons lose energy even more readily. Yet more than 10 cosmic rays (CRs) have been observed with nominal energies at or above $10^{20} \pm 30\%$ eV \[3,4\] with the Fly’s Eye event having $3.2 \times 10^{20}$ eV \[5\]. Elbert and Sommers, using search criteria based on the Hillas condition and other reasonable expectations as to the properties of sources capable of accelerating protons to these high energies, found no sources within 50 Mpc of Earth \[2\]. Thus, it is widely believed that the GZK limit must somehow be violated to explain the origin of the observed UHECRs.

The need for GZK violation is based on the assumption that UHECRs and photons from the same source should arrive from the same general direction and with only a moderate arrival time difference. If this assumption is not valid, the observed UHECRs could be produced by sources within the GZK distance that are not in the direction of the UHECRs and moreover may have evolved significantly between the UHECR production and the emission of the photons we now observe. In this case, the existence of particles with ultra-high energies would not raise a paradox if one or more candidates exist for a “waned” source, within the GZK distance.

The coincidence of an observed UHECR and its astrophysical source depend on the angular deflection of the UHECR being small. The UHECR is deflected by the magnetic fields it encounters which are generally assumed to be of order nG, leading to expected deflections of order a few degrees or less:

$$\delta \theta \sim 0.5^{\circ} \sqrt{D_{\text{Mpc}} \lambda_{\text{Mpc}} (B_{\text{nG}} / E_{20})}$$  \hspace{1cm} (1)

being the rms deflection of a proton of energy $E_{20}10^{20}$ eV traveling a distance $D$ through randomly-oriented patches of magnetic field having rms value $B$ and a scale length $\lambda$ \[3\]. The corresponding difference between the arrival times of photons and UHECR’s, $\tau_{\text{arr}} \sim$
(δθ)²D/2c, is small on astrophysical scales, ≈ 10⁴ yr taking D = L_{\text{GZK}} ≈ 20 Mpc for a E_{20} = 3 proton in a nG average field. With these values both angular and temporal correlations are expected between the photons and UHECRs of a given source.

However, as we show here, extra-galactic magnetic fields (EGMF)’s are plausibly larger by several orders of magnitude than is generally assumed, in which case the angular deflection of UHECRs and the time delay between a UHECR and photons from the same source have been grossly underestimated. With larger fields there is no angular and temporal correlation between a UHECR and its source. The long time delay between the arrival of UHECRs and of photons implies that the source of the UHECRS could be unremarkable or even undetectable today. The expected cutoff in the UHECR spectrum is modified as discussed below.

Several groups have recently explored the possibility that the EGMF has a large scale structure akin to that observed in simulations of dark matter, assuming mean fields in the 0.1-1 µG range [7,8]. Results of our analysis are consistent with these detailed numerical simulations, and clarify the generality of a large EGMF, ≳ few tenths µG, relieving the concern that those results are artifacts of the particular spectra of magnetic inhomogeneities employed (e.g., Kolmogorov [7], log-normal [8]). Subsequent work [9,10] explored these field ansätze to find what parameters give the best fit to the observed spectrum and angular distribution of CRs above 10¹⁹ eV. We instead focus on the puzzling highest energy events, those above 10²⁰ eV. We show that the broad angular distribution and absence of identifiable sources within the GZK volume is not a problem for either GRB or AGN sources. Our discussion focusses on the interpretation of UHECRs as protons since for nuclei the energy attenuation distance via photodissociation is shorter than the GZK length for protons of the same energy. However our results can be applied to nuclei as well.

The structure of this letter is the following. We first determine the Faraday rotation limits on the EGMFs. Next we examine the trajectories of UHE protons in these EGMFs and debunk the notion that the deflection angles of 10²⁰ eV protons must be of order a few degrees or less. This removes the necessity of an angular and temporal correlation between
UHECRs and their astrophysical sources. Finally we show that AGNs or GRBs active in
the local supercluster in the past 10-100 million years can account for the observed UHECR
flux. We conclude with a summary and some observational tests of these scenarios.

**EXTRAGALACTIC MAGNETIC FIELD:** The prime constraint on the EGMF arises
from the Faraday rotation of light from distant quasars [11], for which cosmological effects
must be included. The rotation measure of a source at a redshift \( z \) is

\[
RM(z) = 0.2 \frac{h_{75}^2 \text{rad}}{m^2} \int_0^z \frac{n_{05}(z')B_{\|\mu G}(z')}{(1 + z')^3} \, d\epsilon(z'),
\]

where \( h_{75} \) is the Hubble constant in units of 75 km/sec/Mpc, distances are in Mpc, and \( n_{05} \)
is the electron density in units of \((\Omega_b/0.05)(3H_0^2/8\pi G)/m_p\); \( \Omega_{b,m,\Lambda} \) are the ratios of bary-
onic, matter, and vacuum energy densities to the closure density. The comoving distance
increment, \( d\epsilon \), is related to the physical distance by \( dl = d\epsilon/(1 + z') \). Additional redshift
factors arise due to the RM’s quadratic dependence on frequency and the possible cosmo-
logical evolution of the electron number density \( n_e(z) \equiv n_{05}(1 + z)^p_e \) and the magnetic field
strength \( B(z) \equiv B_0(1 + z)^p_B \). The cosmological “dimensionless effective distance” \( d_p(z) \),
normalized so that \( d_0(z) \) measures the comoving distance in terms of the Horizon distance
2c/H_0 and with \( p \equiv p_e + p_B - 3 \), contains the net effect of the cosmological evolution:

\[
d_p(z) \equiv \int_0^z \frac{dz'(1 + z')^p/2}{[\Omega_m(1 + z')^3 + (1 - \Omega_m - \Omega_\Lambda)(1 + z')^2 + \Omega_\Lambda]^{3/2}}.
\]

In the models below, for \( z = 2.5 \), \( \Omega_\Lambda = 1 - \Omega_m \) and \( \Omega_m = 1 \) (0.3), we encounter \( d_2 = 1.85(2.98) \), \( d_0 = 0.46(0.68) \), and \( d_{-3} = 0.14(0.18) \).

Faraday rotation measurements for constraining the EGMF make use of quasars
with \( \langle z \rangle \approx 2.5 \) and yield \( RM \lesssim 5 \text{ rad m}^{-2} \) [11]. Eqn (2) can be written \( RM_5 =
400 n_{05} B_{\|\mu G} h_{75} \, d_p(z) \), where \( RM(z) \equiv 5 \, RM_5 \text{ rad m}^{-2} \). We now consider two extreme
models of the structure of the EGMF.

**Randomly Oriented Patches:** A commonplace model, which leads to eqn (1), posits that
the EGMF consists of domains of constant but randomly oriented field, much like in a
ferromagnet, with present rms strength \( B_0 \) and characteristic size \( \lambda \) [11]. Assuming that \( n_e \)
and $\lambda$ are constant in co-moving coordinates, and that the energy density of the magnetic field scales like radiation, implies

$$ B_0 = 0.4 \, \mu G \frac{\text{RM}_5}{h_{75}^{3/2} n_{05}} \frac{1}{\sqrt{\lambda_{\text{Mpc}}}} \frac{d_0(z)}{d_2(z)}, \quad (4) $$

where we have taken the mean number of patches in the path to the quasar to be $r_c(z)/\lambda$. Assuming $n_e \approx n_b$ and baryonic closure of the Universe, i.e., $n_{05} \approx 20$, implies nG fields for $\lambda \approx 1 \, \text{Mpc}$ \cite{1} and hence the small deflections generally assumed in discussions of UHECR trajectories. However $n_e$ should be taken at least a factor of 20 smaller than in those estimates, since $\Omega_b \leq 0.05$. Moreover $\Omega_b$ has contributions from neutrons, and only electrons in ionized gas are relevant to Faraday rotation, so this further reduces $n_e$. Taking the more realistic value $n_{05} \approx 0.3$ gives $B_0$ in this model of order $0.5 \, (0.4) \, \text{RM}_5(0.3/n_{05}) \mu G$, for the flat $\Omega_m = 1 \, (0.3)$ cosmologies.

**Sheets and Voids:** It is more likely that the scale structure of the EGMF consists of randomly oriented sheets of field, presumably associated with the sheet-like and filamentary concentrations observed in the matter distribution, separated by relative voids. Idealize this to sheets consisting of layers of thickness $L_S$ within which the field has a constant magnitude $B_0$ and random orientation, separated by voids of thickness $L_0(\approx 50 \, \text{Mpc})$, with $L_S \ll L_0$. Observations of high redshift clusters provide strong evidence that $\Omega_m$ is small and the sheets and voids of matter were largely in place at $z \sim 2.5$ \cite{2}. Therefore we expect no scaling of $B$, $n_e$, and $L_S$ with redshift in the sheet-void model, for the redshifts $\leq 2.5$ relevant for Faraday rotation observations. Thus eqn (4) can be used to obtain $B_0$ in this model by replacing $d_2(z) \rightarrow d_{-3}(z)$ and multiplying by $\sqrt{L_0/L_S}$. Note that $B_0$ and $n_e$ stand for the present rms field strength and electron density *within the sheets* and not averaged over the voids, so $n_e$ can be expected to be enhanced compared to the random-patches model by the factor $L_0/L_S$. Therefore in the sheet-void model we find $B_0$ of order $d_2(2.5)/(d_{-3}(2.5)\sqrt{50})$ times that of the random patches model. This is a factor $\approx 0.9$ in both cosmologies. If the sheets themselves consist of many patches of randomly oriented field of typical size $\lambda$, $B_0$ should be reduced by a factor $\sqrt{\lambda/L_S}$.  

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The Faraday rotation estimate, $B_0 \approx 0.5 \text{ RM} \, \mu \text{G}$, is only an upper limit. However, this value is comparable to the $\approx 1.5 \mu \text{G}$ field argued to exist at the core of the local (Virgo) Supercluster [13] and to field intensities of $\approx 0.2 \mu \text{G}$ observed in Abell 2319 and Coma (see [11] for a review and [14], which appeared after our paper was submitted, for further evidence for such high magnetic fields.). A $\mu \text{G}$ field corresponds approximately to equipartition between the magnetic energy and the gravitational and thermal energies of the supercluster. The consistency of the inferred field from these disparate approaches increases our confidence in the conclusion: The EGMF, at least in the local supercluster, is plausibly of order a few tenths $\mu \text{G}$ rather than nG as has been traditionally assumed. In the random patch approximation the energy density of this field is comparable to that of the CMBR. Therefore we focus primarily on the more likely “sheets and voids” model.

**TRAJECTORIES OF UHE PARTICLES:** The Larmor radius of a proton with an energy $E_{20} \times 10^{20} \text{eV}$ in a constant orthogonal field, $B_\perp$, is

$$R_L = 0.11 \text{ Mpc} \, E_{20}/B_\perp \mu \text{G},$$

(5)
corresponding to a deflection angle of order $\delta \theta \approx 0.5^\circ \, B_\perp \mu \text{G} \, \lambda_{\text{Mpc}}/E_{20}$ when traversing a distance $\lambda \ll R_L$. In the random patches model, we can express the deflection angle directly in terms of the Faraday rotation measure allowing the patch-size and its uncertainty to be eliminated. For a source at a distance $D \gg \lambda$ the relationship is $\delta \theta_{\text{rms}} \approx 60^\circ \, \sqrt{D_{\text{Mpc}}} \, \text{RM}_5/(n_{05} \, E_{20} \, h^{3/2}_{75})$, as long as this deflection is small. An analogous relationship can be obtained for the sheet-void model, however it is only applicable for cosmic rays which traverse many sheets, which is not the case for UHECRs since the GZK length is less than or of order the void size.

Vallée [13] quotes an average coherent enhancement $> 1.2 \mu \text{G}$ in the central 10 Mpc region of Virgo, our local supercluster. There are surely some inhomogeneities at the 0.1 - 1 Mpc scale, if only from the galaxies themselves. In such a field, the minimum energy above which UHECRs have approximately rectilinear motion over a distance of 10 Mpc can be estimated by requiring (1) to evaluate to $\leq 10^9$ with scale size $\lambda = 0.1 \text{ Mpc}$ and
Such small deflection requires \( E \gtrsim 6 \times 10^{21} \) eV, far larger than in the field configurations considered in refs. [8,9], for which particles above \((1 - 2) \times 10^{20} \) eV display rectilinear motion. Given that fields may be larger than previously assumed, we should not rule out the possibility of magnetic confinement, diffusive motion, or large angle scattering for even the highest energy CRs thus far observed.

**IMPLICATIONS FOR UHECR SOURCES:** Now we apply these results to possible sources of UHECRs. We consider either continuous sources (specifically AGNs) or bursting sources (specifically GRBs). In addition to being capable of accelerating the UHECR to the required energy the sources must satisfy two additional constraints. First, the effective number of sources, \( N_{\text{eff}} \), within the effective volume contributing to UHECRs on Earth, \( V_{\text{eff}} \), must be \( \geq 1 \). If \( N_{\text{eff}} < 1 \), it is improbable that a source exists within the GZK distance during a time interval such that its cosmic rays arrive at Earth in the past 30 years. Second, the sources should be energetically capable of producing the observed flux of UHECRS on Earth.

The effective number of active sources within the effective volume satisfies \( N_{\text{eff}} = V_{\text{eff}} \times \rho/\epsilon_s \) for constant sources, and \( N_{\text{eff}} = V_{\text{eff}} \times \Gamma \tau_{\text{arr}} \) for bursting sources. Here \( \rho \) and \( \tau \) are the density and lifetime of active sources, \( \tau_{\text{arr}} \) is the spread in UHECR arrival times, \( \Gamma \) is the rate per unit volume for bursting sources and \( \epsilon_s \) is the “duty-factor” of a long-lived but not eternal source, e.g., \( \epsilon_s = \tau_{\text{arr}}/\min(\tau, \tau_{\text{arr}}) \) for an AGN. The effective volume, \( V_{\text{eff}} \), depends on the magnetic field model. In the sheet-void model, the contributing region is the local supercluster within a distance of \( L_{\text{GZK}} \): if the cosmic ray experiences a few large angle scatterings as it travels from source to Earth, \( V_{\text{eff}} \rightarrow \pi L_{\text{GZK}}^2 D_{\text{LSC}} \), where \( D_{\text{LSC}} \lesssim 10 \) Mpc is the thickness of the local supercluster.

The spectrum of UHECRs above \( 10^{18.5} \) eV can adequately be described by \( E^2 j(E) \approx 3 \text{eVcm}^{-2}\text{s}^{-1}\text{str}^{-1} \), corresponding to an energy flux per decade of energy, \( \Phi_{\text{obs}} \), which is about \( 3 \times 10^{45} \text{ergMpc}^{-2}\text{yr}^{-1}\text{str}^{-1} \). The energy flux per decade in UHECRs, produced by \( N_{\text{eff}} \) sources is:
\[
\Phi = \epsilon_{CR} E_{10} \frac{c \epsilon_s N_{\text{eff}}}{4\pi V_{\text{eff}}},
\]

(6)

where \( E_{10} \) is the energy produced per energy decade in other forms (e.g., gamma-rays) by the source and \( \epsilon_{CR} \) is the relative efficiency of producing an equal energy per decade in UHECRs. For a continuous source, \( E_{10} = P_{10} \tau_{GZK} \), where \( P_{10} \) denotes the power per decade and \( \tau_{GZK} = L_{GZK}/c \).

*AGNs and Hot Spots in Giant Radio Galaxies* are the canonical example of sources that satisfy the Hillas acceleration conditions. However, there are no suitable AGNs within the GZK distance in the directions of the observed UHECRs. If large deflection angles are the norm, the alignment requirement is relaxed and all powerful radio sources within the GZK distance become candidates. Elbert and Sommers [2] list eight such high flux radio galaxies. Among them M87 (and possibly Cen A) are possibly strong enough to satisfy the Hillas condition [17]. These objects and others in the list might also have been more powerful AGNs in the past and thus are candidate sources [2] in this picture.

The UHECR flux from AGNs is computed using eqn 6. The power of a moderate AGN, in the energy decade corresponding to gamma rays, is of order \( 10^{45} \) erg s\(^{-1} \). \( N_{\text{eff}} \) in \( V_{\text{eff}} \) over the past GZK time must be \( \geq 1 \), as discussed above. The energy flux of UHECRs observed on Earth today due to a single AGN in our local supercluster is therefore \( \Phi \approx 10^{48} \) erg Mpc\(^{-2} \) yr\(^{-1} \) \( \epsilon_{CR} \epsilon_s \). Hence from an energetics standpoint there is a comfortable margin for inefficiency or inactivity in the UHECR production by AGNs in the local supercluster.

If M87 is indeed powerful enough to accelerate UHECRs [17], then it is possible that it produces all the observed UHECRs. The different arrival directions simply reflect different trajectories in the EGMF. An alternative scenario is that no source within the GZK limit (or only M87) is active today, but such sources have been active in the past. This implies that the UHECR-producing lifetime, \( \tau_{AGN} \), must be \( \lesssim \tau_{\text{arr}} \sim \tau_{GZK} \). If \( \tau_{AGN} \gg \tau_{GZK} \), it would be unlikely that a source which was active recently enough to have produced an observed UHECR, would no longer appear active. On the other hand, if \( \tau_{AGN} \ll \tau_{GZK} \), the only way
to have $N_{\text{eff}} \geq 1$ is if $\rho_{\text{AGN}} V_{\text{eff}} \gg 1$. If this were the case, we should see many objects which might have been good sources during the last GZK time, while in fact we see just a few. For example, if $\tau_{\text{AGN}}/\tau_{\text{GZK}} = 0.1$, the probability is $\sim 43\%$ that eight sources which have been active within $\tau_{\text{GZK}}$ would all be inactive today, and the probability is $\sim 38\%$ that 1 out of the eight would be active. Thus the likelihood of finding the current situation would be rather large. Therefore, we conclude that $\tau_{\text{AGN}} < \tau_{\text{GZK}} \approx 6 \times 10^7$ yr. Remarkably, independent estimates of AGN lifetimes are in the $10^7$–$10^8$ yr range \[18\], so the AGN source model survives a highly non-trivial requirement.

**GRBs**: GRBs might be beamed with an opening angle $\theta_{\text{GRB}} \approx 1/10$. With such an opening angle we observe only a fraction $\theta_{\text{GRB}}^2/4$ of all bursts. Let $\Gamma_{\text{GRB}}$ be the overall rate of GRBs per unit volume. The observed rate of GRBs, $(\theta_{\text{GRB}}^2/4)\Gamma_{\text{GRB}} = \Gamma_{-9} 10^{-9}$ yr$^{-1}$ Mpc$^{-3}$, is independent of beaming and thus fairly well determined; if gamma ray bursts follow star formation $\Gamma_{-9} \approx 1$ \[10\]. Uniformity requires that the spread in arrival times of UHECRs from a single source is long compared to the time between contributing GRB events. If magnetic fields are of order nG or less, UHECRs experience small angular deflections. Only GRBs beaming toward Earth contribute, $\tau_{\text{arr}} \approx 10^4$ yr, and $N_{\text{eff}}$ is marginal \[15\].

However if the magnetic field is larger and UHECRs experience large deflections, the beaming fraction suppression factor is removed. In addition, $\tau_{\text{arr}}$ increases because of the greater path length; it is replaced by the GZK attenuation time, $\tau_{\text{GZK}}$. If the cosmic ray experiences a few large angle scatterings as it travels from source to Earth, $N_{\text{eff}} \approx 10^5\Gamma_{-9}$ for $E = 3 \times 10^{20}$ eV, and the number of sources is adequate to assure our epoch is not unusual. Eqn 11 gives the energy flux per decade in UHECRs. Taking $E_{10} \approx 10^{52}$ ergs, $L_{\text{GZK}} \approx 60$ Mpc (since $E_{20} \approx 1$ dominates the spectrum of UHECRs) and making the optimistic assumptions that $(\theta_{\text{GRB}}^2/4)^{-1} = 200$ and $\epsilon_{\text{CR}} = 1$, gives $\Phi \approx 10^{46}\text{erg Mpc}^{-2}\text{yr}^{-1}\text{str}^{-1}$. Thus, Gamma Ray Bursts are viable, but not by a large factor, from this standpoint.

**PREDICTIONS OF THIS SCENARIO**: Several clusters of 2-3 events having energies from $\approx 4$–$30 \times 10^{19}$ eV have been observed \[9\]. If the ultra-high energy part of the cosmic ray spectrum consists of protons which experience large deflections due to few-tenth-$\mu$G fields
in the local supercluster, this must be a statistical fluke. Even if UHECRs are produced in a handful of locations within the GZK distance, this initial localization will not survive subsequent deflection, which is large and strongly energy dependent without fine-tuning of the fields. Thus clustering or the possible directional correlation with distant compact radio quasars \[13\] would be evidence against the picture advanced here.

If M87 is the source of all UHECRs, several consequences follow from its being located near the center of the local supercluster, at a distance of 20 Mpc which is approximately the GZK distance for a \(3 \times 10^{20}\) eV proton. When better statistics allow the spectrum to be investigated at higher energy a cutoff in energy should be evident in the data. Additionally, if, as expected, the effective scattering distance is not too small compared with the supercluster dimensions we should find an “in-out” asymmetry with respect to the center of the local supercluster. Southern Hemisphere detectors, looking outward with respect to the local supercluster, would be expected to see a lower UHE flux than observed in the Northern Hemisphere. Since not much increase in pathlength can be tolerated for particles originating near the GZK distance, we could infer in this case that magnetic fields are not as strong as are allowed by Faraday Rotation and equipartition limits. If, instead, GRBs or multiple AGNs are the source of UHECRs, the energy cutoff would be softer than with a single source but the in-out asymmetry might still appear if the sources were concentrated near the supergalactic center.

A striking aspect of this picture is that observed CRs come mainly from the local supercluster: at ultra-high energy their range is limited by the GZK effect, while at lower energy they are confined near their sources by the relatively strong fields. This may lead to a unified explanation for the knee and ankle structures in the CR spectrum; a more complete treatment of the overall spectrum remains to be addressed in future work.

In summary, we have shown that the highest energy cosmic rays can originate in the local supercluster, either from an AGN which now may appear past its prime or from gamma ray bursts which have occurred in the last 10-100 million years. We presented two distinct models of the structure of extragalactic magnetic fields, and recalled observational data on
the field in our own and nearby superclusters, which indicate that extragalatic magnetic fields can be of order $\mu$G rather than the nG heretofore generally assumed. This radically changes the picture of ultra-high energy cosmic rays and implies that even the highest energy cosmic rays observed to date have strongly bent trajectories such that i) there is no directional correlation with the source; ii) there is no temporal correlation between UHECRs and photons from a given source, on time scales relevant for identifying the sources, even for AGNs, and iii) the power in UHECRs which can be supplied by the relevant superposition of sources contributing over a GZK time, $\approx 10^8$ yr, is easily adequate for AGNs and may barely be adequate for GRBs.

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