

Auger Test of the Cen A Model of Highest Energy Cosmic Rays

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If, as recently proposed by Farrar and Piran, Cen A is the source of cosmic rays detected above the Greisen-Zatsepin-Kuz'min cutoff, neutrons are ≈ 140 more probable than protons to be observed along its line of sight. This is because the proton flux is rendered nearly isotropic by $\mathcal{O}(\mu\text{G})$ intergalactic magnetic fields. With the anticipated aperture of the Southern Auger Observatory, one may expect on the order of 2 neutron events/year above 10^{20} eV in the line of sight of Cen A.

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The energy spectrum of cosmic rays (CRs) is well fitted by power laws with an increasing index for energies above 4×10^{15} eV (the “knee”) flattening again above 5×10^{18} eV (the “ankle”), yielding the overall shape of a leg. Over the last third of the last century, ingenious installations with large effective areas and long exposure times—needed to overcome the steep falling flux—have raised the tail of the spectrum up to an energy of 3×10^{20} eV, with no evidence that the highest energy recorded thus far is Nature’s upper limit [1]. The origin of these extraordinarily energetic particles continues to present a major enigma to high energy physics [2].

The main problem posed by the detection of CRs of such energy (if nucleons, gammas, and/or nuclei) is energy degradation through inelastic collisions with the universal radiation fields permeating the universe. Therefore, if the CR sources are all at cosmological distances, the observed spectrum must virtually end with the Greisen-Zatsepin-Kuz'min (GZK) cutoff at $E \approx 8 \times 10^{19}$ eV [3]. The spectral cutoff is less sharp for nearby sources (within 50 Mpc or so). The arrival directions of the trans-GZK events are distributed widely over the sky, with no plausible counterparts (such as sources in the Galactic plane or in the local supercluster). Furthermore, the data are consistent with an isotropic distribution of sources in sharp contrast to the anisotropic distribution of light within 50 Mpc [4]. The difficulties encountered by conventional acceleration mechanisms in accelerating particles to the highest observed energies have motivated suggestions that the underlying production mechanism could be of a nonacceleration nature. Namely, charged and neutral primaries, mainly light mesons (pions) together with a small fraction (3%) of nucleons, might be produced at extremely high energy by the decay of supermassive elementary X particles ($m_X \sim 10^{22} - 10^{28}$ eV) [5]. However, if this were the case, the observed spectrum should be dominated by γ rays and neutrinos, in contrast to current observation [6]. Alternative explanations involve undiscovered neutral hadrons with masses above a few GeV [7], neutrinos producing nucleons and photons via resonant Z production with the relic neutrino background [8], or else neutrinos attaining cross sections in the millibarn range above the electroweak

scale [9]. A controversial correlation between the arrival direction of CRs above 10^{20} eV and high redshift compact radio quasars seems to support these scenarios [10].

Over the past few years, it has become evident that the observed near-isotropy of arrival directions can be easily explained if even the highest energy cosmic rays propagate diffusively, camouflaging a unique source only a few Mpc away [11]. Within this framework, the particles experience large deflections through randomly oriented patches of strong magnetic fields $\mathcal{O}(\mu\text{G})$ [12,13]. Recently, Farrar and Piran (FP) [14] noted that an extragalactic magnetic field of $\sim 0.3 \mu\text{G}$ would bend CR paths sufficiently, allowing one to trace back trans-GZK orbits from the Earth’s northern hemisphere to the southern radio galaxy Cen A. Moreover, they show that the flux of Cen A at 10^{19} eV (at Earth) is comparable to that of all other sources in the Universe, strongly supporting the single-source hypothesis. If this is the case, and the absence of the GZK cutoff is a reflection of our coincidental position near Cen A ($d \approx 3.4$ Mpc), it must be that the emission of uncharged particles from Cen A should render an enhancement of the CR flux in the southern hemisphere.

Cen A is a complex Fanaroff-Riley (FR) I [15] radio-loud source ($l \approx 310^\circ, b \approx 20^\circ$) identified at optical frequencies with the galaxy NGC 5128 [16]. The radio morphology is intricate with large nonthermal radio lobes. In particular, the structure of the northern middle lobe resembles the “hot spots” which exist at the extremities of FR-II galaxies [17], although for Cen A the brightness contrast (hot spot to lobe) is not as extreme as in, e.g., Cyg A [18]. The energetics of acceleration in hot spots were discussed in [19]. The criteria were applied in [20] to show the plausibility of attaining trans-GZK energies in the hot spot of Cen A. Moreover, EGRET measurements [21] of the γ ray flux for energies > 100 MeV allow an estimate $L_\gamma \sim 10^{41}$ erg s^{-1} for the source [22]. This value of L_γ is consistent with an earlier observation in the TeV range during a period of elevated activity [23], and is considerably smaller than the estimated bolometric luminosity $L_{\text{bol}} \sim 10^{43}$ erg s^{-1} [16].

CR “lore” convinces us that the TeV γ -ray emission is a result of synchrotron radiation of electrons or protons of

still higher energy [24,25]. Strictly speaking, the observed γ radiation is related to (i) the development of pair cascades triggered by secondary photopion products that cool instantaneously via synchrotron radiation and (ii) the synchrotron radiation of protons itself that becomes a very effective channel to produce high energy γ rays above 10^{19} eV. There are plausible physical arguments [25,26] as well as some observational reasons [27] to believe that, when proton acceleration is being limited by energy losses, the CR luminosity $L_{CR} \approx L_\gamma$. The low ratio L_γ/L_{bol} thus leads us to assume that both ultrahigh energy CRs and γ production take place in the lobes with the bulk of the softer radiation coming from the core.

Following FP we introduce ϵ , the efficiency of ultrahigh energy CR production compared to high energy γ production—from the above, we expect $\epsilon \approx 1$. Using equal power per decade over the interval 1×10^{19} eV $< E < 4 \times 10^{20}$ eV, we estimate a source luminosity

$$\frac{E^2 dN_0^{p+n}}{dEdt} \approx 1.7\epsilon L_{41} \times 10^{52} \text{ eV/s}, \quad (1)$$

where $L_{41} \equiv$ luminosity of Cen A per 10^{41} erg s^{-1} and the subscript “0” refers to quantities at the source.

Ignoring energy losses for the moment, the density of protons at the present time t of energy E at a distance r from Cen A (assumed to be continuously emitting at a constant spectral rate $dN_0^{p+n}/dEdt$ from time t_{on} until the present) is

$$\begin{aligned} \frac{dn(r,t)}{dE} &= \frac{dN_0^{p+n}}{dEdt} \frac{1}{[4\pi D(E)]^{3/2}} \int_{t_{on}}^t dt' \frac{e^{-r^2/4D(t-t')}}{(t-t')^{3/2}} \\ &= \frac{dN_0^{p+n}}{dEdt} \frac{1}{4\pi D(E)r} I(x), \end{aligned} \quad (2)$$

where $D(E)$ stands for the diffusion coefficient, $x = 4DT_{on}/r^2 \equiv T_{on}/\tau_D$, $T_{on} = t - t_{on}$, and

$$I(x) = \frac{1}{\sqrt{\pi}} \int_{1/x}^{\infty} \frac{du}{\sqrt{u}} e^{-u}. \quad (3)$$

In each “scatter,” the diffusion coefficient describes an independent angular deviation of particle trajectories whose magnitude depends on the Larmor radius $R_L = 100E_{20}/B_{\mu G}$ kpc, where $E_{20} = E/10^{20}$ eV, $B_{\mu G} = B/(1 \mu G)$. Extragalactic magnetic field strengths and coherence lengths are not well established, but it may be plausible to assume a Kolmogorov form for the turbulent magnetic field power spectrum with coherent directions on scales of 0.5–1 Mpc. One can then naively estimate that protons with energies $E < 10^{21} \ell_{Mpc} B_{\mu G}$ eV remain trapped inside magnetic subdomains of size ℓ , attaining efficient diffusion when the wave number of the associated Alfvén wave is equal to the gyroradius of the particle [28]. With a Kolmogorov spectrum this gives, for a diffusion coefficient [29],

$$D(E) \approx 0.048(E_{20} \ell_{Mpc}^2 / B_{\mu G})^{1/3} \text{ Mpc}^2/\text{Myr}. \quad (4)$$

Here, $\ell_{Mpc} = \ell/(1 \text{ Mpc})$. For $T_{on} \rightarrow \infty$, the density approaches its time-independent equilibrium value n_{eq} , while for $T_{on} = \tau_D = r^2/4D$, $n/n_{eq} = 0.16$.

A word about the validity of the diffusive approximation: one may easily check that for $E = 10^{19}$ eV, $B = 0.5 \mu G$, and $\ell = 0.5$ Mpc, the diffusive distance traveled $c\tau_D = 50$ Mpc $\gg d = 3.4$ Mpc. For higher energies, the validity of the diffusive approach must be checked on a case-by-case basis [30]. For these purposes, in the case of a continuously emitting source, the definition of a diffusion time is somewhat arbitrary. We will use τ_D , a choice consistent with simulations [31].

To further constrain the parameters of the model, we evaluate the energy-weighted approximately isotropic proton flux at 1.5×10^{19} eV, which lies in the center of the flat “low energy” region [14] of the spectrum:

$$\begin{aligned} E^3 J_p(E) &= \frac{Ec}{(4\pi)^2 d D(E)} \frac{E^2 dN_0^{p+n}}{dEdt} I(t/\tau_D) \\ &\approx 7.6 \times 10^{24} \epsilon L_{41} I \text{ eV}^2 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \end{aligned} \quad (5)$$

In the second line of the equation, we have used the values of B and ℓ as given in the previous paragraph. We fix $\epsilon L_{41} I = 0.40$, after comparing Eq. (5) to the observed CR flux: $E^3 J_{obs}(E) = 10^{24.5} \text{ eV}^2 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [1]. With $\epsilon L_{41} \approx 1$, this determines $I \approx 0.40$ and, consequently, the required age of the source T_{on} to be about 400 Myr [32]. To maintain flux at the “ankle” for the same T_{on} , we require an approximate doubling of L_{CR} at 5×10^{18} eV. Because of the larger diffusive time delay at this energy, this translates into an increased luminosity in the early phase of Cen A. The associated synchrotron photons are emitted at energies < 30 MeV [33]. The increase in radiation luminosity in this region is not inconsistent with the flattening of the spectrum observed at lower energies [34].

In current models describing cosmic ray acceleration, the principal mechanisms for energy loss are synchrotron radiation and photopion processes [24,25]. If the radiation energy density of the source is sufficiently high, photopion production leads to copious neutron flux (that can readily escape the system) and the associated degradation of the proton spectrum. This occurs only near the maximum proton energy [24]. It is reasonable to assume that the ambient photon density of Cen A is sufficiently high [20] so that near the end of the spectrum the efficiency of neutron production ϵ_n becomes comparable to the proton channel ϵ_p . We take for granted that the proton spectrum cuts off at 4×10^{20} eV. Consequently, because of the leading particle effect [19], we expect a cutoff in the neutron spectrum at approximately 2×10^{20} eV. We adopt an energy of 1×10^{20} eV as a lower cutoff on the neutron spectrum, and simplify the discussion by assuming that in the narrow interval $E_{20} \in [1, 2] \epsilon_n \approx \epsilon_p$. The neutron spectrum observed at Earth is further narrowed because of decay *en route*. The decay length is $\lambda(E) = 0.9E_{20}$ Mpc

[35]. Because of the exponential depletion, about 2% of the neutrons survive the trip at 10^{20} eV, and about 15% at 2×10^{20} eV. We note at this point that the increasing survival of neutrons at energies above 1.5×10^{20} eV shows, as a consequence of the Cen A model, that the observed diffuse flux $E^3 J_{\text{obs}}(E)$ should begin to decrease at these energies (unless other factors contribute to an increase).

We may now estimate a signal-to-noise ratio for the detection of neutron CRs in the southern hemisphere, say, at Auger [36]. If we assume circular pixel sizes with 2° diameters, the neutron events from Cen A will be collected in a pixel representing a solid angle $\Delta\Omega(\text{Cen A}) \approx 10^{-3}$ sr. For Auger ($S = 3000$ km² detector with aperture 7000 km² sr above 10^{19} eV), the event rate of (diffuse) protons coming from the direction of Cen A (say, in a 2° angular cone) is found to be

$$\begin{aligned} \frac{dN_p}{dt} &= S\Delta\Omega(\text{Cen A}) \int_{E_1}^{E_2} E^3 J_p(E) \frac{dE}{E^3} \\ &\approx S\Delta\Omega(\text{Cen A}) \langle E^3 J_p(E) \rangle / (2E_1^2) \\ &\leq 0.014/E_{1,20}^2 \text{ events/yr,} \end{aligned} \quad (6)$$

where we have assumed $E^3 J_p(E)$ to be (approximately) constant up to at least $E \approx 3 \times 10^{20}$ eV, in agreement with the observed isotropic flux in this region, $E^3 J_{\text{obs}}(E) = 10^{24.5 \pm 0.2}$ eV² m⁻² s⁻¹ sr⁻¹ [1]. The neutron rate

$$\begin{aligned} \frac{dN_n}{dt} &= \frac{S}{4\pi d^2} \int_{E_1}^{E_2} \frac{dN_0^n}{dEdt} e^{-d/\lambda(E)} \\ &= \frac{S}{4\pi d^2} \int_{E_1}^{E_2} \frac{E^2 dN_0^n}{dEdt} \frac{dE}{E^2} e^{-d/\lambda(E)} \\ &= 116\epsilon_n L_{41} \int_{E_{1,20}}^{E_{2,20}} \frac{dE_{20}}{E_{20}^2} e^{-d/\lambda(E)} \text{ events/yr,} \end{aligned} \quad (7)$$

is potentially measurable. For $E_{20} \in [1, 2]$ we expect

$$dN_n/dt \approx 4\epsilon_n L_{41} \text{ events/yr} \quad (8)$$

arriving from the Cen A direction of the sky. With $\epsilon_n L_{41} \approx 1/2$, this gives about two direct events per year, against the negligible background of Eq. (6) [37]. Thus, in a few years running (of Auger), the FP hypothesis of Cen A as the primary source of all trans-GZK CRs *can be directly tested*.

We now address the question of anisotropy. This can be found by computing the incoming current flux density $D\nabla n$ as viewed by an observer on Earth, and one finds for a continuously emitting source a distribution $\sim(1 + \alpha \cos(\theta))$ about the direction of the source at angle θ to the zenith, where

$$\alpha = 2D(E)(cr)^{-1}(I'/I). \quad (9)$$

Here,

$$I'(x) = \frac{1}{\sqrt{\pi}} \int_{1/x}^{\infty} du \sqrt{u} e^{-u}, \quad (10)$$

with $x = T_{\text{on}}/\tau_D$, and I was defined in Eq. (3) [38]. For our choices of B and ℓ , $T_{\text{on}} = 400$ Myr, we find for $E = 10^{19}$ eV ($E = 10^{20}$ eV) that $\alpha = 0.04$ ($\alpha = 0.07$).

All in all, the Southern Auger Observatory will be in a gifted position to explore Cen A, providing in a few years of operation sufficient statistics to probe extragalactic magnetic fields below the present observational upper limit $\mathcal{O}(\mu\text{G})$. The potential detection of the neutrons at Auger can subsequently be validated by the larger aperture EUSO and OWL orbiting detectors [39]. Additionally, if FP's hypothesis is confirmed, it would constitute robust evidence that all FR radiogalaxies produce extremely high energy CRs. Furthermore, our next-door radiogalaxy could provide a profitable arena for particle physics.

In closing, we wish to comment briefly on some published CR observations relevant to this paper. A small excess of flux at 10^{15} eV (detected at the Buckland Park field station [40]) that reached the Earth preferentially from the direction of Cen A could militate against FP's hypothesis. At this energy the photon flux will be completely damped through interactions with the cosmic microwave background [41]. Therefore, if CRs propagate diffusively one expects no deviation from isotropy on the (extragalactic) CR spectrum (except for a neutrino flux peaked along the line of sight). However, as far as we are aware, such anisotropy was not confirmed by the Sydney University Giant Air Shower Recorder (SUGAR) [42]. Furthermore, the random arrival directions of the southern highest energy CRs seem to back up the above-outlined model.

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