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Update on tests of the Cen A neutron-emission model of highest energy cosmic rays

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We propose that neutron emission from Cen A dominates the cosmic ray sky at the high end of the spectrum. Neutrons that decay generate proton diffusion fronts, whereas those that survive decay produce an angular spike in the direction of the source. We use recent data reported by the Pierre Auger Collaboration to normalize the injection spectrum and estimate the required luminosity in cosmic rays. We find that such a luminosity, $L_{\rm CR} \sim 3.2 \times 10^{40}$ erg/s, is comfortably smaller than the bolometric luminosity of Cen A, $L_{\rm bol} \sim 10^{43}$ erg/s. We compute the incoming current flux density as viewed by an observer on Earth, and we show that the anisotropy amplitude is in agreement with data at the 1σ level. Regardless of the underlying source model, our results indicate that after a decade of data taking the Pierre Auger Observatory will be able to test our proposal.

About a decade ago we put forward the idea of using neutrons as markers of ultrahigh energy cosmic ray (UHECR) emission from Cen A [1]. In this Brief Report we update our proposal to accommodate recent observations.

The HiRes Collaboration has reported a suppression of the CR flux above $E_{\rm s}^{\rm HR} = 56 \pm 5({\rm stat}) \pm 9({\rm syst})$ EeV [2]. The spectral index γ of the flux, $J \propto E^{-\gamma}$, steepens from 2.81 ± 0.03 to 5.1 ± 0.7. This suppression has been confirmed by the Pierre Auger Collaboration, measuring $\gamma = 2.69 \pm 0.2({\rm stat}) \pm 0.06({\rm syst})$ and $\gamma = 4.2 \pm 0.4({\rm stat}) \pm 0.06({\rm syst})$ below and above $E_{\rm s}^{\rm A} = 40$ EeV, respectively (the systematic uncertainty in the energy determination is estimated as 22%) [3]. In addition, an intriguing CR excess was found in the direction towards Cen A, a powerful radiogalaxy at $d = 3.4$ Mpc [4]. Out of the 69 Auger events with $E_1 > 55$ EeV (collected over 6 yr but equivalent to 2.9 yr of the nominal exposure/yr of the full Auger), the overdensity with largest significance is 13 CRs within 18° from Cen A, versus only 3.2 expected if the flux were isotropic. Furthermore, 2 of the events arrived within less than 3° of the radiogalaxy. Within errors, we set $E_{\rm s}^{\rm HR} \simeq E_{\rm s}^{\rm A} \simeq E_1$, and take the spectrum to fall approximately as $J \propto E^{-4}$ above the onset of the suppression.

HiRes has presented evidence that the CR composition remains protons up to the highest energies [5]. Auger data on the depth of shower maximum $X_{\rm max}$, its rms fluctuation $\sigma(X_{\rm max})$, and muon rates at ground level favor a heavy composition like ^{56}Fe [6]. A critical assumption of our hypothesis is that the primaries of the highest energy Auger data are protons (and neutrons) and not ^{56}Fe. We note that some arguments have appeared recently which lend support to the hypothesis of proton primaries. One is the reasoning [7] that if particles responsible for the Cen A excess are heavy nuclei (say ^{56}Fe), then a similar (as yet unobserved [8]) anisotropy with better statistics should be present among protons at $E_1/26 \sim 2$ EeV energies. A second is that modeling reveals that $X_{\rm max}$ and $\sigma(X_{\rm max})$ in themselves may be poor estimators of primary composition [9]. In [10] it is shown that the ratio $(k \equiv \Lambda/\lambda)$ of the measured shower attenuation length (Λ) to the interaction length of protons in the atmosphere (λ) is likely poorly estimated in shower codes, and poorly assigned in various CR experiments. The assumption of a single value 1.26 ± 0.03 [10] for k, and proton primaries, is shown to give excellent agreement with all CR data as of 2007. The rate and fluctuations of early shower development (related to depth of first interaction X_1, inelasticity K, mean multiplicity $\langle n \rangle$, and depth of most inelastic interaction X_n) are the physics behind the deviation of k from unity. In [11] it is shown that the simple combination $X_{\rm max} - \sigma(X_{\rm max})$ is a superior estimator of composition than $X_{\rm max}$ or $\sigma(X_{\rm max})$ individually. The combination is much less sensitive to data features that can skew interpretation, such as fluctuations in X_1 and tails in the $X_{\rm max}$ distribution. Furthermore, when this new estimator is applied to the HiRes and Auger data, both data sets find agreement with a primary spectrum of protons [11]. Thus, we feel that the assumption herein that UHECR primaries hitting the Earth's atmosphere are protons and neutrons is viable.

We propose that neutron emission from Cen A dominates the observed CR flux above the suppression [1]. (The acceleration process of the parent proton population is discussed in Appendix A.) Neutrons that decay generate the proton diffusion fronts. The Bohm diffusive regime is usually described by an energy-dependent diffusion coefficient, $D = 0.1\ (E_{\rm EeV}/B_{\rm nG})$ (Mpc^2/Myr). Charged particles with $E \gtrsim E_c = d_{\rm Mpc}\, B_{\rm nG}$ EeV propagate along a straight lines, whereas particles with $E \lesssim E_c$ diffuse [12]. For an extragalactic magnetic field $B_{\rm nG} = 50$ (see Appendix B), protons even up to the highest observed energies undergo Bohm diffusion. As a result of this diffusion, an injection spectrum of $dN_0/dEdt \propto E^{-3}$ in the region of the source cutoff, results in a spectrum $J \propto E^{-4}$ for the protons at Earth. The rate at Earth for the surviving neutrons is

$$\frac{dN_n}{dt} = \frac{S}{4\pi d^2} \int_{E_1}^{E_2} e^{-d/\lambda(E)}\ \frac{dN_0}{dEdt}\, dE, \qquad (1)$$

where $\lambda(E) \sim (E/10^{20}{\rm eV})$ Mpc is the neutron decay length and S is the area of the surface detector

(= 3000 km^2 for Auger). For the energy interval between $E_1 = 55$ EeV and $E_2 = 150$ EeV, we calculate the normalization factor using the observation of 2 neutrons in 3 yr. We then use this normalization factor to calculate the luminosity of the source in the above energy interval. We find $L_{\rm CR}^{(E_1,E_2)} = 9 \times 10^{39}$ erg/s. Next, we assume continuity of the spectrum at E_1 as it flattens at lower energy to E^{-2}. Taking the lower bound on the energy to be $E_0 = 1$ EeV, we can then fix the luminosity for this interval and find $L_{\rm CR}^{(E_0,E_1)} = 4 \times 10^{40}$ erg/s. Adding these, we find the (quasi) bolometric luminosity to be $L_{\rm CR}^{(E_0,E_2)} = 5 \times 10^{40}$ erg/s, which is about a factor of 2 smaller than the observed luminosity in γ-rays, $L_\gamma \approx 10^{41}$ erg/s [13] in the interval 100 MeV $< E <$ 10 GeV.

To further constrain the parameters of the model, we evaluate the energy-weighted approximately isotropic (diffuse) proton flux at 70 EeV. The value of this diffuse flux depends on the energy threshold E_1 above which Cen A is the dominate source (55 EeV here), on the spectral index at the source (-3 here), on the nature of diffusion (Bohm here), and on the on-time $T_{\rm on}$ of the source [1]. We obtain $\langle E^4\, J\rangle = 1.6 \times 10^{57}$ eV^3 km^{-2} yr^{-1} sr^{-1}, in agreement with observations [3], for a source actively emitting UHECRs over $T_{\rm on} \gtrsim 70$ Myr. (We note that the minimum $T_{\rm on}$ is similar to the diffusion time $T_D(E) \sim d^2/[4D(E)] \sim 20$ Myr at $E = 70$ EeV and $B_{\rm nG} = 50$.) If we assume circular pixel sizes with 3° radii, the neutrons will be collected in a pixel representing a solid angle $\Delta\Omega \simeq 8.6 \times 10^{-3}$ sr. The proton rate coming from the direction of Cen A is

$$\frac{dN_p}{dt} = S\ \Delta\Omega \int_{E_1}^{E_2} \langle E^4\, J\rangle\, \frac{dE}{E^4} = 0.08 \text{ events/yr}\,. \quad (2)$$

It is important to stress that the 3° window does not have an underlying theoretical motivation. Recall that this angular range resulted from a scan of parameters to maximize Auger's signal significance. Cen A covers an elliptical region spanning about 10° along the major axis. Therefore, some care is required to select the region of the sky which is most likely to maximize the signal-to-noise [14].

We now address the question of anisotropy. Duplicating the analysis of [1] for Bohm diffusion on a 50 nG B-field we determine the amplitude of a dipole term aligned with Cen A, the so-called "asymmetry parameter" α. For $E = 70$ EeV we obtain $\alpha = 0.29$, within 1σ of the same anisotropy amplitude $\alpha = 0.25 \pm 0.18$ obtained from the arrival directions of the 69 observed events [15].

One caveat is that we assumed that neutrons completely dominate the ultrahigh energy Cen A emission spectrum; that is

$$\frac{dN_0}{dE\, dt} = (N_0^n + N_0^p) E^{-3}\,, \quad \text{with} \quad N_0^p/N_0^n \ll 1\,. \quad (3)$$

This reduces the number of free parameters in the model. The actual proton-to-neutron fraction depends on the properties of the source, especially the ratio of photon-to-magnetic energy density.

In summary, existing data is consistent with the hypothesis that Cen A dominates the CR sky at the high end of the spectrum [16]. The Pierre Auger Observatory is in a gifted position to explore Cen A and will provide in the next 9 yr of operation sufficient statistics to test this hypothesis. We expect about 6 additional direct neutron events against an almost negligible background [17].

The potential detection of neutrons at Auger can subsequently be validated by the larger aperture of space-based UHECR experiments. The JEM-EUSO mission is scheduled to launch in 2017, and remain operational aboard the International Space Station for 3 or 5 years. Including the 20% duty cycle and 50% Southern versus Northern hemisphere exposure, one expects 60-100 events within 18° of Cen A for the three-year JEM-EUSO mission, and therefore 9-15 direct neutrons. For the five-year mission, numbers are proportionately higher. Work on the implications of our Cen A model for the JEM-EUSO mission is in progress [14].

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Appendix A: UHECR emission from Cen A

Cen A is a complex radio-loud source identified at optical frequencies with the galaxy NGC 5128 [18]. Radio observations at different wavelengths have revealed a rather complex morphology. It comprises a compact core, a jet (with subluminal proper motion $\beta_{\rm jet} \sim 0.5$ [19]) also visible at X-ray frequencies, a weak counter-jet, two inner lobes, a kpc-scale middle lobe, and two giant outer lobes. The jet would be responsible for the formation of the northern inner and middle lobes when interacting with the interstellar and intergalactic media, respectively.

In order to ascertain the capability of Cen A to accelerate UHECR protons one first applies the Hillas criterion [20] for localizing the Fermi engine in space, *i.e* that the Larmor radius be less than the size of the magnetic region. From this condition we infer a maximum CR energy of

$$E \simeq B_{\mu{\rm G}}\, R_{\rm kpc}\ {\rm EeV}\,. \quad ({\rm A1})$$

Furthermore, since the magnetic field carries with it an energy density $B^2/8\pi$ and the flow carries with it an energy flux $> \beta\, c\, B^2/(8\pi)$, (A1) also sets a lower limit on the rate

$$L_B > \frac{1}{8}\, \beta_{\rm jet} c R_{\rm kpc}^2 B_{\mu{\rm G}}^2 \quad ({\rm A2})$$

at which the energy is carried by the out-flowing plasma, and which must be provided by the source [21]. The minimum total power of the jets inflating the giant lobes of Cen A is estimated to be $\approx 8 \times 10^{43}$ erg/s [22]. This argument provides a conservative upper limit for the magnetic field in the jet with kpc-scale radius, $B_{\mu \rm G} \lesssim 50$, and through (A1) leads to $E = 50$ EeV [23].

Of particular interest here, it was recently noted that shear acceleration [24] could help push proton energies up to and beyond 50 EeV [25]. The limb-brightening in the X-ray jet together with the longitudinal magnetic field polarization in the large scale jet might be indicative of internal jet stratification, *i.e.* a fast spine surrounded by slower moving layers. Energetic particles scattered across such a shear flow can sample the kinetic difference in the flow and will naturally experience an additional increase in energy. It is therefore of interest to explore the extreme case, in which protons that diffuse from the inner shock region into the outer shear layers charge-exchange to produce neutrons with $E_2 \sim 150$ EeV. (We let experiment be the arbiter of this proposed mechanism.)

Appendix B: Extragalactic Magnetic Field

Surprisingly little is actually known about the extragalactic magnetic field strength. There are some measurements of diffuse radio emission from the bridge area between the Coma and Abell superclusters [26], which under assumptions of equipartition allows an estimate of $\mathcal{O}(0.2 - 0.6)\,\mu$G for the magnetic field in this region. Fields of $\mathcal{O}(\mu{\rm G})$ are also indicated in a more extensive study of 16 low redshift clusters [27]. It is assumed that the observed B-fields result from the amplification of much weaker seed fields. However, the nature of the initial week seed fields is largely unknown. There are two broad classes of models for seed fields: cosmological models, in which the seed fields are produced in the early universe, and astrophysical models, in which the seed fields are generated by motions of the plasma in (proto)galaxies. Galactic winds are an example of the latter. If most galaxies lived through an active phase in their history, magnetized outflows from their jets and winds would efficiently pollute the extragalactic medium. The resulting B-field is expected to be randomly oriented within cells of sizes below the mean separation between galaxies, $\lambda_B \lesssim 1$ Mpc.

Extremely weak unamplified extragalactic magnetic fields have escaped detection up to now. Measurements of the Faraday rotation in the linearly polarized radio emission from distant quasars [28] and/or distortions of the spectrum and polarization properties in the cosmic microwave background (CMB) [29, 30] imply upper limits on the extragalactic magnetic field strength as a function of the reversal scale. It is important to stress that Faraday rotation measurements (RM) sample extragalactic magnetic fields of any origin (out to quasar distances), while the CMB analyses set limits *only* on primordial magnetic fields. The RM bounds depend significantly on assumptions about the electron density profile as a function of the redshift. When electron densities follow that of the Lyman-α forest, the average magnitude of the magnetic field receives an upper limit of $B \sim 10^{-9}$ G for reversals on the scale of the horizon, and $B \sim 10^{-8}$ G for reversal scales on the order of 1 Mpc [31]. As a statistical average over the sky, an all pervading extragalactic magnetic field is constrained to be [32]

$$B \lesssim 3 \times 10^{-7} \left(\frac{\Omega_b h^2}{0.02}\right)^{-1} \left(\frac{h}{0.72}\right) \left(\frac{\lambda_B}{\rm Mpc}\right)^{1/2} {\rm G}\,, \quad \text{(B1)}$$

where $\Omega_b h^2 \simeq 0.02$ is the baryon density and $h \simeq 0.72$ is the present day Hubble expansion rate in units of 100 km/sec/Mpc. (This is a somewhat conservative bound because Ω_b has contributions from neutrons as well as from protons, but only electrons in ionized gas are relevant to Faraday rotation.)

Very recently it was pointed out that the study of the energy-energy-correlation (EEC) in a given sample of UHECRs can provide important clues on the all pervading extragalactic magnetic field [33]. Since it is expected that UHECRs are accelerated at discrete sources, the deflection in cosmic magnetic fields would result in an energy ordering in the distribution of arrival directions. The Pierre Auger Collaboration has recently released their analysis of EEC [34]. The measured EEC distribution is compatible with the expectation from isotropic arrival directions, *i.e.* no energy-ordered deflections are observed near the most energetic UHECRs. Such an uncorrelated distribution can be caused either by a high source density for an isotropic source distribution or by large deflections of the UHECRs in cosmic magnetic fields. Since the nearby distribution of matter is anisotropic we conclude that the second option is more viable. One interpretation of Auger data on EEC uses the PARametrized Simulation Engine for Cosmic rays (PARSEC), to obtain a lower bound of 10 nG at 95% CL on an all–pervading extragalactic magnetic field with coherence length $\lambda_B = 1$ Mpc, assuming a source density $\leq 10^{-4}$ Mpc^{-3} [35]. This agrees with the results of [36]. Use of these numbers should be regarded as tentative while awaiting additional data and further independent analyses.

[1] L. A. Anchordoqui, H. Goldberg and T. J. Weiler, Phys. Rev. Lett. **87**, 081101 (2001) [arXiv:astro-ph/0103043].

[2] R. U. Abbasi *et al.* [HiRes Collaboration], Phys. Rev. Lett. **100**, 101101 (2008) [arXiv:astro-ph/0703099].

[3] J. Abraham *et al.* [Pierre Auger Collaboration], Phys. Rev. Lett. **101**, 061101 (2008) [arXiv:0806.4302].

[4] P. Abreu *et al.* [Pierre Auger Collaboration], Astropart. Phys. **34**, 314 (2010) [arXiv:1009.1855].

[5] R. U. Abbasi *et al.* [HiRes Collaboration], Phys. Rev. Lett. **104**, 161101 (2010) [arXiv:0910.4184 [astro-ph.HE]].

[6] J. Abraham *et al.* [Pierre Auger Collaboration], Phys. Rev. Lett. **104**, 091101 (2010) [arXiv:1002.0699 [astro-ph.HE]].

[7] M. Lemoine and E. Waxman, JCAP **0911**, 009 (2009) [arXiv:0907.1354].

[8] P. Abreu *et al.* [Pierre Auger Collaboration], JCAP **1106**, 022 (2011) [arXiv:1106.3048 [astro-ph.HE]].

[9] Auger data on $\sigma(X_{\rm max})$ have been recently interpreted in terms of a 2-component (p + Fe) composition, assuming partial abundances f_i that change smoothly with energy: $f_p(E) = f_p(1 \text{ EeV})[1 - \log(E/\text{EeV})/1.5]$. The data favor $f_p(1 \text{ EeV}) = 0.4$. S. Ostapchenko, arXiv:1010.0137 [astro-ph.HE]. Such a persistent rise of the iron content in the vicinity of the ankle ($1 \text{ EeV} < E < 3 \text{ EeV}$) seems to be in disagreement with Auger measurements of the $X_{\rm max}$ distribution.

[10] M. M. Block, Phys. Rev. **D76**, 111503 (2007) [arXiv:0705.3037 [hep-ph]]; M. M. Block, F. Halzen, T. Stanev, Phys. Rev. **D62**, 077501 (2000) [hep-ph/0004232].

[11] G. Wilk and Z. Wlodarczyk, J. Phys. G **38**, 085201 (2011) [arXiv:1006.1781 [astro-ph.HE]].

[12] G. Sigl, M. Lemoine and P. Biermann, Astropart. Phys. **10**, 141 (1999) [arXiv:astro-ph/9806283].

[13] P. Sreekumar, D. L. Bertsch, R. C. Hartman, P. L. Nolan and D. J. Thompson, Astropart. Phys. **11**, 221 (1999) [arXiv:astro-ph/9901277].

[14] L. A. Anchordoqui, P. Denton, H. Goldberg, and T. J. Weiler, in preparation.

[15] The amplitude measurement of the first harmonic modulation in the right-ascension distribution has been computed using the classical Rayleigh formalism weighted by exposure described in P. Abreu *et al.* [Pierre Auger Collaboration], Astropart. Phys. **34**, 627 (2011) [arXiv:1103.2721 [astro-ph.HE]]. The declination dependence of the relative exposure has been taken from P. Sommers, Astropart. Phys. **14**, 271 (2001) [arXiv:astro-ph/0004016].

[16] G. R. Farrar and T. Piran, arXiv:astro-ph/0010370.

[17] Our model also predicts no directional signals from M87.

[18] F. P. Israel, Astron. Astrophys. Rev. **8**, 237 (1998).

[19] M. J. Hardcastle, D. M. Worrall, R. P. Kraft, W. R. Forman, C. Jones and S. S. Murray, Astrophys. J. **593**, 169 (2003) [arXiv:astro-ph/0304443].

[20] A. M. Hillas, Ann. Rev. Astron. Astrophys. **22**, 425 (1984).

[21] E. Waxman, Phys. Scripta **T121**, 147 (2005) [arXiv:astro-ph/0502159].

[22] C. D. Dermer, S. Razzaque, J. D. Finke and A. Atoyan, New J. Phys. **11**, 065016 (2009) [arXiv:0811.1160 [astro-ph]].

[23] The actual size of the acceleration region can be larger because of uncertainties in the angular projection of this region along the line of sight. For example, an explanation of the apparent absence of a counter-jet in Cen A via relativistic beaming suggests that the angle of the visible jet axis with respect to the line of sight is at most 36°, which could lead to a doubling of the jet radius; N. Junkes, R. F. Haynes, J. I. Harnett, and D. L. Jauncey, Astron. Astrophys. **269**, 29 (1993) [Erratum, *ibid* **274**, 1009 (1993)]. On the other hand, equipartition arguments seem to indicate that a field strength of 100 μG in the inner region of the jet is plausible; M. Honda, Astrophys. J. **706**, 1517 (2009) [arXiv:0911.0921 [astro-ph.HE]]. The jet power required to maintain these extreme values of $B_{\mu\rm G}$ and $R_{\rm kpc}$ can be reached during flaring intervals, see [22]. We conclude that acceleration of UHECR protons up to somewhat beyond 100 EeV is therefore in principle possible during powerful episodes of jet activity.

[24] F. M. Rieger and P. Duffy, Astrophys. J. **617**, 155 (2004) [arXiv:astro-ph/0410269].

[25] F. M. Rieger and F. A. Aharonian, arXiv:0910.2327 [astro-ph.HE].

[26] K.-T. Kim, P. P. Kronberg, G. Giovannini and T. Venturi, Nature **341**, 720 (1989).

[27] T. E. Clarke, P. P. Kronberg and H. Böhringer, Astrophys. J. **547**, L111 (2001).

[28] P. P. Kronberg, Rept. Prog. Phys. **57**, 325 (1994).

[29] J. D. Barrow, P. G. Ferreira and J. Silk, Phys. Rev. Lett. **78**, 3610 (1997) [arXiv:astro-ph/9701063].

[30] K. Jedamzik, V. Katalinic and A. V. Olinto, Phys. Rev. Lett. **85**, 700 (2000) [arXiv:astro-ph/9911100].

[31] P. Blasi, S. Burles and A. V. Olinto, Astrophys. J. **514**, L79 (1999) [arXiv:astro-ph/9812487].

[32] G. R. Farrar and T. Piran, Phys. Rev. Lett. **84**, 3527 (2000) [arXiv:astro-ph/9906431].

[33] M. Erdmann and P. Schiffer, Astropart. Phys. **33**, 201 (2010) [arXiv:0904.4888 [astro-ph.HE]].

[34] P. Abreu *et al.* [Pierre Auger Collaboration], arXiv:1107.4805.

[35] P. Schiffer, PhD Thesis, RWTH Aachen University, May 2011; `http://darwin.bth.rwth-aachen.de/opus3/volltexte/2011/3698/`

[36] L. A. Anchordoqui and H. Goldberg, Phys. Rev. D **65**, 021302 (2002) [arXiv:hep-ph/0106217].