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Centaurus A (Cen A) is the nearest radio-loud AGN and is detected from radio to very high energy gamma-rays. Its nuclear spectral energy distribution (SED) shows a double-peak feature, which is well explained by the leptonic synchrotron + synchrotron self-Compton model. This model however cannot account for the observed high energy photons in the TeV range, which display a distinct component. Here we show that $\sim$ TeV photons can be well interpreted as the π^0 decay products from $p\gamma$ interactions of Fermi accelerated high energy protons in the jet with the seed photons around the second SED peak at $\sim$ 170 keV. Extrapolating the inferred proton spectrum to high energies, we find that this same model **is consistent with the detection of 2 ultra-high-energy cosmic ray events detected by Pierre Auger Observatory from the direction of Cen A.** We also estimate the GeV neutrino flux from the same process, and find that it is too faint to be detected by current high-energy neutrino detectors.

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I. Introduction. — Centaurus A (Cen A or NGC 5128) is the nearest active radio galaxy with a distance of approximately 3.5 Mpc and redshift $z = 0.002$ [1]. Although by active galactic nuclei (AGN) standard its bolometric luminosity is not very large, because of its proximity to earth it is one of the best studied AGN. Optically, Cen A is an elliptical galaxy undergoing late stages of a merger event with a small spiral galaxy. Sufficiently large amount of photometric data are available to build a well sampled spectral energy distribution (SED) of Cen A. The emission from the nucleus of Cen A has been observed throughout the electromagnetic spectrum from radio to gamma-rays [2–6], which shows that Cen A has a FR I morphology with two radio lobes, and is a non-blazar source with a jet inclination in the range of 15º to 80º. The nuclear SED shows two peaks, one in the far-infrared band ($\sim 4 \times 10^{-2}$ eV) and another at around 170 keV [7]. In the framework of the unification scheme of AGN, blazars and radio galaxies [8–10] are intrinsically the same objects, viewed at different angles with respect to the jet axis. The double-peak SED structure observed in Cen A is similar to that of blazars whose jets beam towards earth, suggesting that the same spectral feature is also expected from misaligned jet sources such as Cen A. The leading interpretation is the single-zone synchrotron and synchrotron self-Compton (SSC) model. In this scenario, the multi wavelength emission originates from the same region. The low-energy emission in radio to optical wavelengths is the non-thermal synchrotron radiation from a population of relativistic electrons in the jet, while high-energy emission from X-rays to very high energy (VHE) gamma-rays are from the Compton scattering of the above seed synchrotron photons by the same population of electrons. This model is found very successful in explaining the multi-wavelength emission from BL Lac objects and FR I galaxies such as NGC 1275

and M87 [8, 9]. Applying it to Cen A, one found that it is successful in explaining most of the multi wavelength SED data [6, 11]. The difficulty, on the other hand, is the multi-TeV emission detected by HESS during 2004 to 2008 [5]. **Even though the HESS data alone can be fitted by a power law [5], and the entire $10^6 - 10^{13}$ eV spectrum may be still accommodated within one single power law model, a clear dip around 10^{10} eV revealed by Fermi indicates an excess of TeV emission from the extrapolation of the Fermi data [6] (Fig.1). So far this TeV spectral component is not well interpreted within the published leptonic models [6, 11].**

On the other hand, Cen A has long been proposed as the source of very high energy cosmic rays. Recently Pierre Auger Collaboration reported two UHECR events fall within 3.1º around Cen A [12]. By assuming that the two events are from Cen A, the expected high energy neutrino event rates in detectors such as IceCube [13, 14] and the diffuse neutrino flux from Cen A [15] have been estimated. The flux of high energy cosmic rays as well as the accompanying expected secondary photons and neutrinos are calculated from hadronic models [16].

The astrophysical objects producing UHECRs also produce high energy γ-rays due to interaction of the cosmic rays with the background through pp or $p\gamma$ interactions [16–20]. In this letter, we show that the multi-TeV γ-ray emission from Cen A can be naturally interpreted by a hadronic model invoking $p\gamma$ interactions between Fermi-accelerated protons in the jet and the seed photons near the SSC peak (170 keV). **The same model is found consistent with the detection of 2 UHECR events from Cen A.**

II. Hadronic model of TeV gamma-rays. Observations of variable, non-thermal high energy emission from AGNs imply that these sources are efficient accelerators

of particles through shock or diffusive Fermi acceleration processes. While efficient electron acceleration is limited by high radiative losses, protons and heavy nuclei can reach UHE through the same acceleration mechanism. In general, these energetic charged particles (electrons and protons) have a power-law spectrum given as $dN/dE \propto E^{-\alpha}$, with the power index $\alpha \geq 2$ [21, 22].

The dominant $p\gamma$ interaction is through the Δ-resonance, i.e.

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0, & \text{fraction } 2/3 \\ n\,\pi^+ \rightarrow ne^+\nu_e\nu_\mu\bar{\nu}_\mu, & \text{fraction } 1/3 \end{cases} , \quad (1)$$

which has a cross section $\sigma_\Delta \sim 5 \times 10^{-28}\,cm^2$. The charged π's subsequently decay to charged leptons and neutrinos, while neutral π's decay to GeV-TeV photons. For interactions at Δ-resonance, the matching condition is $E'_p\epsilon'_\gamma \simeq 0.32\,(1 - \cos\theta)^{-1}\,\mathrm{GeV}^2$, where E'_p and ϵ'_γ are the proton and the background IC photon energies in the comoving frame of the jet, respectively. Since in the comoving frame the protons collide with the IC photons from all directions, in our calculation we consider an average value $(1 - \cos\theta) \sim 1$ (θ in the range of 0 and π). Denoting Γ as the bulk Lorentz factor of the jet, and $\mathcal{D} = \Gamma^{-1}(1 - \beta\cos\theta_{\mathrm{ob}})^{-1}$ as the Doppler factor to the observer (θ_{ob} is the angle between the observer and the jet direction, and $\beta = v/c$ is the dimensionless speed of the jet), **one can re-write the matching condition as**

$$E_p\epsilon_\gamma \simeq 0.32\,\Gamma\mathcal{D}\,\mathrm{GeV}^2 \ . \quad (2)$$

Here $\epsilon_\gamma = \mathcal{D}\epsilon'_\gamma/(1+z)$ is the observed photon energy, while $E_p = \Gamma E'_p/(1+z)$ is the energy of the proton as measured by an earth observer, if it could escape the source (instead of producing π_0 photons) and reach earth without energy loss. This is because the proton energy in the rest frame of the AGN central engine (in which the jet is observed to move with a Lorentz factor Γ) is $\Gamma E'_p$. An earth observer is at rest of this frame, but with an additional effect due to cosmic expansion. This definition of E_p is not of significance in calculating the TeV photon spectrum, but is more convenient to discuss UHECRs (see III). In (2), the $(1+z)$ parameter has been neglected due to the small redshift $z = 0.002$ of the source.

In the comoving frame, each pion carries ~ 0.2 of the proton energy. Considering each π^0 splits into two γ-rays, the π^0-decay γ-ray energy in the observer frame can be written as $E_\gamma = \mathcal{D}E'_p/10 = (\mathcal{D}/10\Gamma)E_p$. The matching condition between the π^0-decay photon energy and the target photon energy is therefore

$$E_\gamma\epsilon_\gamma \simeq 0.032\,\mathcal{D}^2\,\mathrm{GeV}^2 \ , \quad (3)$$

Modeling Cen A suggests a viewing angle θ_{ob} between 15° to 80° [11, 23]. The Doppler factor $\mathcal{D}$ is found in the range of 0.12 - 3.7 [6, 10, 11, 24]. In the following, we

adopt a nominal model of [6], with the following parameters: $\mathcal{D} = 1$, $\Gamma = 7$, the comoving blob size $\mathcal{R}'_b = 3 \times 10^{15}$ cm, and the comoving magnetic field strength $B' = 6.2$ G, but keep parameter dependences in the formulae. This model fits well (the green curve in Fig.1) the bulk of observed photon flux starting from the low energy regime to 10s of GeV. The second SED peak (SSC) is at $\epsilon_\gamma^p \simeq 170$ keV with the corresponding observed photon energy flux $F_\gamma(\epsilon_\gamma^p) = 9.0 \times 10^{-10}$ erg cm^{-2} s^{-1} [25]. It is clearly shown from Fig.1 that the model cannot account for the observations in higher energies.

Adopting $\mathcal{D} = 1$, the target peak photon energy $\epsilon_\gamma^p = 170$ keV is matched by $E_p^p \sim 13$ TeV and $E_p^p \sim 190$ GeV for the Δ-resonance condition (Eq.(2) and (3)). The typical photon energy E_γ^p is in the energy range of HESS detection. The optical depth of the Δ-resonance process in the emission region can be estimated as $\tau_{p\gamma} = n'_\gamma\sigma_\Delta\mathcal{R}'_b$, where n'_γ is the comoving photon number density in the jet, which is given as $n'_\gamma = \eta(L_\gamma/\mathcal{D}^\kappa)/[4\pi\mathcal{R}'^2_b c(\epsilon_\gamma/\mathcal{D})]$, with $\kappa \sim (3-4)$ (depending on whether the jet is continuous or discrete) and $\eta \sim 1$. At $\epsilon_\gamma^p = 170$ keV, the observed photon luminosity is $L_\gamma(\epsilon_\gamma^p) = 1.32 \times 10^{42}\,(d/3.5\,\mathrm{Mpc})^2$ erg s^{-1}. For $\mathcal{D} = 1$, this gives $n'_\gamma(\epsilon_\gamma^p) \sim 1.4 \times 10^6$ cm$^{-3}(d/3.5\,\mathrm{Mpc})^2(\mathcal{R}'_{b,15.5})^{-2}\mathcal{D}^{-\kappa+1}$ and $\tau_{p\gamma}(\epsilon_\gamma^p) \sim 2.1 \times 10^{-6}(d/3.5\,\mathrm{Mpc})^2(\mathcal{R}'_{b,15.5})^{-1}\mathcal{D}^{-\kappa+1}$.

The photon energy flux $F_\gamma(E_\gamma^p)$ (effectively the E^2dN/dE spectrum at $E = E_\gamma^p$) is related to the total proton number in the source. The total electron number can be constrained based on the synchrotron+SSC modeling. However, since we do not know the composition of the jet, especially the lepton-to-proton number ratio (pair multiplicity), one cannot calculate $F_\gamma(E_\gamma^p)$ from the available data. We therefore derive it through fitting the high energy photon spectrum.

Once $F_\gamma(E_\gamma^p)$ is fitted from the data, one can calculate the spectrum of the π^0-decay hadronic component, which depends on the spectra of the protons and of the target photons. We assume that protons have a power law distribution $N(E_p)dE_p \propto E_p^{-\alpha}dE_p$. Since the number of π^0-decay photons at a particular energy depends on the number of protons and optical depth, i.e. $N(E_\gamma) \propto N(E_p)/\tau_{p\gamma} \propto N(E_p)n'_\gamma(\epsilon_\gamma)$ (where E_γ, E_p, ϵ_γ satisfy the matching conditions (2) and (3)), one can calculate the π^0-decay spectrum through the scaling

$$\frac{F_\gamma(E_\gamma)}{F_\gamma(E_\gamma^p)} = \frac{n'_\gamma(\epsilon_\gamma)}{n'_\gamma(\epsilon_\gamma^p)}\left(\frac{E_\gamma}{E_\gamma^p}\right)^{-\alpha+2} , \quad (4)$$

where we have used the relation $E_p/E_p^p = E_\gamma/E_\gamma^p$, and the power index +2 converts the photon number spectrum to energy spectrum. We fix the proton spectral index to $\alpha = 3.08$. **This index is found to well fit the HESS data in the high energy regime, and it is also the typical cosmic ray spectral index in the UHECR regime. At the energy $E_p^p \sim 13$ TeV (which corresponds to the $E_\gamma^p \sim 190$ GeV peak of the hadronic component), the proton luminosity at ~ 13 TeV is $L_p(E_p^p) \sim (15/2)L_\gamma(E_\gamma^p)[\tau_{p\gamma}(\epsilon_\gamma^p)]^{-1} \sim$**
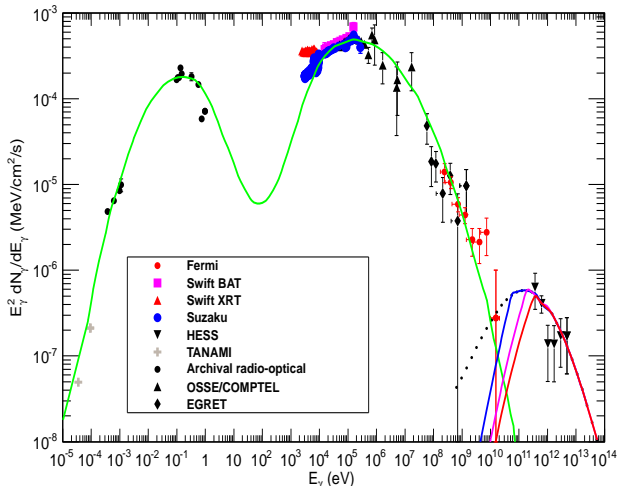
FIG. 1. The observed spectral energy distribution $E_\gamma^2 \frac{dN_\gamma}{dE_\gamma}$ (or F_γ) from the Cen A core region. Colored symbol points are observations (with different sources marked in the figure), and the curves are model fits: The green curve is synchrotron + SSC fit from Abdo et. al. [6], **while the blue, magenta, and red curves are the hadronic emission component due to π^0-decay with $E_p^b = 4, 13, 25$ TeV, respectively. The case of no proton spectral break (black dashed line) is plotted for comparison.**

4.0×10^{45} erg s$^{-1}(d/3.5$ Mpc$)^{-2}\mathcal{R}'_{b,15.5}\mathcal{D}^{\kappa-1}$. **This is smaller than the Eddington luminosity of the central black hole $L_{Edd} \sim 1.3 \times 10^{46}$ erg s$^{-1}(M/10^8 M_\odot)$. In order not to violate the energy budget constraint posted by the Eddington luminosity, it is required that the proton energy spectrum should break to a harder index (e.g. $\alpha \sim 2$) at low energies. In our calculation, we introduce a break energy E_p^b, so that $\alpha = 2$ for $E_p < E_p^b$, and $\alpha = 3.08$ for $E_p > E_p^b$. We numerically calculate the model spectrum. As can be seen from Fig.1, the hadronic model spectrum, along with the leptonic spectrum, can well interpret the observational data above GeV for a wide range of E_p^b values (from 4-25 TeV).**

For $E_\gamma < E_\gamma^p$, the Δ-resonance matching condition (Eq.(3)) requires $\epsilon_\gamma > \epsilon_\gamma^p = 170$ keV. The drop of the target photon flux then results in a decreasing photon flux. **The harder proton spectrum below E_p^b strengthens the effect.** The same applies to $E_\gamma > E_\gamma^p$, whose target photons have $\epsilon_\gamma < \epsilon_\gamma^p$. Since the number of protons increases with decreasing energy (power law distribution), the real energy flux peak of the hadronic component is slightly smaller than $E_\gamma^p = 190$ GeV.

III. UHECR flux. The same model can be used to estimate the expected UHECR flux from Cen A. The maximim energy to which cosmic rays can be accelerated is constrained by the size of the emitting region and the magnetic field in it. For Cen A, one has [29]

$$E_{p,max} = 4 \times 10^{19} \left(\frac{B'}{6.2\,G}\right)\left(\frac{t_v}{10^5 s}\right)\left(\frac{\Gamma}{7}\right) \text{ eV}, \quad (5)$$

where $t_v \sim 1$ day is the observed variability timescale, which determines the size of the emission region, and the best-fit values of B' and Γ of the leptonic model parameters have been adopted. Above this energy the number of cosmic rays should follow an exponential decay. Bearing in mind the uncertainties in the viewing angle, it is possible that the maximum proton energy can reach 57 EeV or even higher for a same Doppler factor $\mathcal{D}$ (but with a larger Γ). In the following, we assume that $E_{p,max}$ is extended to 57 EeV.

Within our model, based on the flux at E_γ^p one can estimate the cosmic ray flux at E_p^p. One out of $\tau_{p\gamma}^{-1}$ protons interact with the target photons to produce gamma-rays through π^0 decay. So the proton flux $F_p(E_p)$ at proton energy E_p is related to the high energy photon flux $F_\gamma(E_\gamma)$ at the photon energy E_γ through

$$F_p(E_p) = 7.5 F_\gamma(E_\gamma)[\tau_{p\gamma}(E_p)]^{-1} . \quad (6)$$

The factor 7.5 comes from the fact that the Δ-resonance has 2/3 probability to decay to the $p\pi^0$ channel as shown in Eq.(1), and each pion carries 20% of the proton energy. At $E_\gamma^p = 190$ GeV, the best fit model flux is $F_\gamma(E_\gamma^p) \sim 6.6 \times 10^{-13}$ erg s^{-1} cm^{-2}. Since the proton energy flux $F_p \propto E_p^{-\alpha+2}$, we obtain the source proton luminosity at any energy E_p through

$$\frac{F_p(E_p)}{F_p(E_p^p)} = \left(\frac{E_p}{E_p^p}\right)^{-\alpha+2} . \quad (7)$$

Plugging in $E_p = 57$ EeV, and $E_p^p = 13$ TeV, we obtain the UHECR flux above 57 EeV as $F_p(57 \text{ EeV}) = 1.6 \times 10^{-13}$ erg s^{-1} cm^{-2}.

The Pierre Auger Observatory (PAO) reported that there are roughly 10 UHECR events above 57 EeV concentrated around the Centaurus direction, a region with a high AGN density [26–28]. Two of these events were found to fall within 3 degrees from Cen A [12], suggesting the evidence that Cen A may be the first UHECR source.

We can estimate the expected number of UHECR proton events above 57 EeV detectable by the PAO array [26, 27]. Taking Cen A as a point source, the integrated exposure of PAO is $\Xi = 9000/\pi$ km^2. One has to also consider the relative exposure $\omega(\delta)$ for the angle of declination δ. For Cen A, $\delta = 47°$, and the corresponding value is $\omega(\delta) \simeq 0.64$[14]. The time duration for data collection by PAO is about 15/4 yr between 1st January 2004 and August 2007. So the expected total number of UHECR proton event above 57 EeV is

$$\#\text{Events} = \frac{\zeta F_p(57\text{E}eV)}{57\text{EeV}}\Xi\omega(\delta)\frac{15}{4}\text{yr} = 3.7\zeta, \quad (8)$$

where ζ denotes the fraction of UHECRs that can escape from the source region. We can see for a reasonable

value $\zeta \sim 50\%$, the predicted value 1.9 matches nicely the detected 2 events from PAO.

Interperting the 2 UHECRs as associated to Cen A implies that the intergalactic magnetic fields have a strength weaker than 10^{-12} G. This is consistent with a dipole extrapolation of the galactic magnetic fields, but is inconsistent with a wind (r^{-2}-dependence) extrapolation.

VI. High energy neutrinos. From the decay mode of Eq.(1), we can see that the fluxes of neutral and charged pions have the relation $F(\pi^0) = 2F(\pi^+)$. Since each neutrino shares $1/4$ of the π^+ energy, while each photon shares $1/2$ of the π^0 energy, the energy relationship between a γ-ray and a neutrino produced by protons of same energy satisfies $E_\nu = E_\gamma/2$. The neutrino energy flux can be estimated as $F_\nu = (3/4)F_{\pi^+} \sim (3/8)F_{\pi^0} = (3/8)F_\gamma$. The maximum neutrino flux is therefore $F_\nu^p \simeq 2.5 \times 10^{-13}$ erg s^{-1} cm$^{-2} \simeq 1.5 \times 10^{-10}$ GeV s^{-1} cm^{-2}, with a typical energy $E_\nu^p = E_\gamma^p/2 \simeq 95$ GeV. This flux level is well below the current neutrino flux upper limit imposed by IceCube [30].

VII. Discussion. **We have proposed a hadronic model to interpret both the TeV data and the two UHECR events detected from Cen A. The model requires a relatively high proton-to-electron luminosity ratio (of order $10^3 - 10^4$), with the proton luminosity close to the Eddington luminosity of the black hole. On the other hand, in view of the sharp dependence of L_p on $\mathcal{D}$ and the uncertainties in modeling of the leptonic component, such a scenario can be validated for a choice of reasonable parameters. An alterative way of accounting for the TeV component through a hadronic component may be through invoking photon-pair cascade initiated from UHECR $p\gamma$ interactions [31] which is beyond the scope of this Letter.**

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