Very high-energy gamma-ray signature of ultrahigh-energy cosmic-ray acceleration in Centaurus A

Jagdish C. Joshi1*, Luis Salvador Miranda 1, Soebur Razzaque1† and Lili Yang2,†

1 Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa
2 Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 13, Nova Gorica, Slovenia

ABSTRACT
The association of at least a dozen ultrahigh-energy cosmic-ray (UHECR) events with energy \(\gtrsim 55 \text{ EeV}\) detected by the Pierre Auger Observatory (PAO) from the direction of Centaurus-A, the nearest radio galaxy, supports the scenario of UHECR acceleration in the jets of radio galaxies. In this work, we model radio to very high energy (VHE, \(\gtrsim 100 \text{ GeV}\)) \(\gamma\)-ray emission from Cen A, including GeV hardness detected by Fermi-LAT and TeV emission detected by HESS. We consider two scenarios: (i) Two zone synchrotron self-Compton (SSC) and external-Compton (EC) models, (ii) Two zone SSC, EC and photo-hadronic emission from cosmic ray interactions. The GeV hardness observed by Fermi-LAT can be explained using these two scenarios, where zone 2 EC emission is very important. Hadronic emission in scenario (ii) can explain VHE data with the same spectral slope as obtained through fitting UHECRs from Cen A. The peak luminosity in cosmic ray proton at 1 TeV, to explain the VHE \(\gamma\)-ray data is \(\approx 2.5 \times 10^{46} \text{ erg/s}\). The bolometric luminosity in cosmic ray protons is consistent with the luminosity required to explain the origin of 13 UHECR signal events that are correlated with Cen A.

Key words: Radio Galaxy : Active Galactic Nuclei, Cosmic Rays, Multi-Wavelength Emission

1 INTRODUCTION
Centaurus A (Cen A) or NGC 5128 is a radio galaxy (elliptical shape) of FR-I type [Fanaroff & Riley (1974)] with inner X-ray jet of order 1 kpc (Israel 1998), located at a distance of 3.7 Mpc (Ferrarese et al. 2007). This galaxy has two giant radio lobes with \(10^7\) light years length along the north-south direction in the sky (Feain et al. 2018). The substructures in Cen A, like inner lobes and jets have been studied in radio wavelength and X-ray band. The radio observations detected a subluminal motion \((v \sim 0.5c)\) in the 100 pc length of the jet (Hardcastle et al. 2003). This analysis assumes jet-counterjet symmetry in Cen A, and estimates that the jet makes an angle \(\theta_{\text{ob}} = 15^\circ\) with the line of sight (l.o.s.) of the observer. Another study of Cen A uses the bright jet subluminal motion \((v \sim 0.1c)\) and constraints that the jet axis can be in between \(50^\circ - 80^\circ\) w.r.t. the l.o.s. of the observer (Tingay et al. 1998). In this work, we consider \(\theta_{\text{ob}} = 30^\circ\), which has been used in the SSC modelling of Cen A (Abdo et al. 2010). The central region activity of Cen A is powered by a supermassive black hole whose mass has been estimated using the gas kinematics around Cen A (Neumayer et al. 2007), and matches the more recent update on its mass of value \((5.5 \pm 3.0) \times 10^7 M_\odot\) (Cappellari et al. 2009) using the stellar kinematics studies. This provides the Eddington luminosity for Cen A of value \(L_{\text{Edd}} = (0.7 \pm 0.4) \times 10^{46}\) erg/s.

The detection of \(\gamma\)-rays from Cen A started in 1970s (Grindlay et al. 1975; Hall et al. 1976) and continued until 1990s (Sreekumar et al. 1999). In the last decade, more data from this object have been detected in MeV-GeV \(\gamma\)-rays by the Fermi satellite (Abdo et al. 2010) and in the VHE range by ground based Cherenkov telescopes (Rowell et al. 1999; Aharonian et al. 2009). Using 4 years of Fermi-LAT data of Cen A, Sahakyan et al. (2013) discovered that the \(\gamma\)-ray spectrum becomes harder above approximately 4 GeV. In 2007, the PAO correlated two cosmic ray events within \(3.1^\circ\) of Cen A (Abraham et al. 2007). Until 2015, in 10 years of PAO data events above 55 EeV (from the central \(18^\circ\) region of Cen A) are correlated to this source, where 3.2 events are expected from the isotropic background (Aab et al. 2015). This correlation has been increased to 19 events in 2017, where 6 events are expected from the isotropic background (Aab et al. 2017).

Observations of Cen A, before the discovery of GeV hardness in 2013 (Sahakyan et al. 2013), are well explained using one zone SSC models (Chiaberge et al. 2001; Abdo et al. 2010) and in multi-zone SSC models (Lenain et al. 2008), if the HESS observation is not taken into account (Aharonian et al. 2009). Roustazadeh & Bottcher (2011) considered \(\gamma - \gamma\) interactions in the internal jet and associated cascade emission to explain the
2 LEPTONIC EMISSION MODELS

The SED peaks of Cen A, at 10^{-1} eV (infrared), and at 170 keV (soft γ rays) are reasonably explained by the leptonic models (Chiaberge et al. 2001; Abdol et al. 2010; Petropoulou et al. 2014). We use a publicly available code by Krawczynski et al. (2004) to calculate SSC and EC radiative losses. In this code the input parameters of the model are the redshift z of Cen A, the size of the emitting blob R_0, energy density of electrons in this blob w_c, magnetic field B, the jet angle w.r.t. the observer θ_{ab}, and a spectrum of electrons with a break energy. We estimate the spectrum of thermal photons from the disk, EC with the disk photons and the SSC process in the jet of Cen A. The SSC parameters B, R_0, θ_{ab}, bulk-Lorentz factor of the jet (Γ) and Doppler factor (δ_D = [Γ(1−β cos(θ_{ab}))]^{-1}), where β is the speed of the relativistic jet, are listed in Table 1. The injected spectrum of electrons follows a break power law with spectral index β from minimum electron energy E_{e,br} to the break energy E_{e,br} and p2 from E_{e,br} to the maximum electron energy E_{e,max}, as

\[
\frac{dN_e}{dE_e} = N_0 \left\{ \begin{array}{ll} \frac{E_e}{E_{e,br}}^{-p1} ; & E_e \leq E_{e,br} \\ \frac{E_e}{E_{e,br}}^{-p2} ; & E_e > E_{e,br} \end{array} \right. \tag{1}
\]

The γ-ray flux in the SSC model is produced due to interaction of theses electrons with target photons available in the jet of Cen A. Similarly in the EC model γ-rays are produced by the interaction of high energy electrons with the target radiation field available outside the jet, which is from the accretion disk.

3 PHOTO-HADRONIC MODEL

Cen A is a probable source of UHECRs as seen in the PAO association of ≥ 55 EeV events towards its location. Acceleration of cosmic ray protons upto 50 GeV can occur via shear acceleration in the jet of Cen A (Rieger & Aharonian 2009) while diffusive shock acceleration in the jet of Cen A can accelerate protons up to 100 GeV (Honda 2009). If L is the apparent isotropic luminosity of Cen A at a radius R, and if a fraction ε_B of this luminosity goes into magnetic field and a fraction ε_e = L_e/L into electrons, then the maximum energy of the particles with atomic number Z, accelerated in Cen A, (Dermer et al. 2009; Dermer & Razzaque 2010) is given by,

\[
E_{\text{max}} \approx 2 \times 10^{20} Z \frac{\sqrt{(ε_B/ε_e)βL/10^{46} \text{erg/s}}}{Γ} \quad \text{eV} \tag{2}
\]

The maximum energy of cosmic rays in Cen A can also be derived by Fermi-acceleration in colliding shells using the apparent source power L and the bulk Lorentz factor of the shells Γ, Γ_a (Dermer et al. 2009),

\[
E_{\text{max}} \approx 2.4 \times 10^{20} Z \frac{Γ_a}{Γ} \frac{Γ}{4} \sqrt{ε_B L/10^{46} \text{erg/s}} \quad \text{eV} \tag{3}
\]

The emission from Cen A is reported in quiescent state and the photo-hadronic models to explain this scenario can be adopted from the earlier models (Sahu et al. 2014, 2017). The energy of a photon for Cen A, in comoving frame (denoted by t) and in the observer frame (no superscript) are related by E_{γ} = δ_D E'_γ/(1 + z). The kinematical condition E_{γ,γ'} ≈ 0.032 \frac{E_{e,br}^2}{(ε_B/ε_e) GeV^2} relates the photons of energy E_{γ} produced via pion decay during the p − γ interactions, to the target photons of energy ε_γ. We use a broken power-law for proton distribution but here, for mathematical expressions, we have shown the formalism for an individual segment of the power law. For the protons with energy E_p it is given as,

\[
\frac{dN_p}{dE_p} = C_p E_p^{−α}, \tag{4}
\]

with a spectral index α ≥ 2. These protons interact with the target photons and create neutral pions which decay to γ-rays. The number of π^{+}−decay photons at a given energy is proportional to both the number of high energy protons and the density of the SSC background photons in the jet, i.e. N(E_γ) = C_γ N_p(E_p)n_γ(E_γ). The γ-ray flux from the π^{0} decay is then given by \(E_γ \Phi_{SSC}(E_γ) = C_p C_γ (10Γ/δ_D)^{1−α} n'_γ(E_γ) E_γ^{2−α} \) (5).

In terms of the SSC photon energy and its luminosity, the photon number density n_γ' is expressed as

\[
n'_γ(E_γ) = \frac{N_γ}{δ_D^{2+κ} 4π R_0^2 c_γ}, \tag{6}
\]

where \(κ \sim 1.0, \) κ describes whether the jet is continuous (κ = 0) or discrete (κ = 1) (Sahu et al. 2012). The SSC photon luminosity is expressed in terms of the observed flux \(Φ_{SSC}(E_γ) = c_γ^2 dN_γ/d\epsilon_γ \) and is given by,

\[
L_{γ,SSC} = \frac{4πd^2 Φ_{SSC}(E_γ)}{(1 + z)^2}. \tag{7}
\]

The \(Φ_{SSC} \) is calculated using the leptonic model. Taking the ratio of fluxes at two energies, using Eq. (5) and kinematic condition, the flux for an energy E_γ takes the form (Sahu et al. 2017),

\[
F(E_γ) = A_γ \Phi_{SSC}(E_γ) \left( \frac{E_γ}{\text{GeV}} \right)^{−α+3}. \tag{8}
\]

The optical depth of the Δ-resonance process with cross section \(σ_Δ = 5 \times 10^{-26} \text{cm}^2 \) is \(τ_{p,Δ} = n'_c σ_Δ R_0^2. \) In this picture, one out of \(τ_{p,Δ}^{-1} \) protons, interacts with the SSC background to produce
Fermi accelerated high energy protons and photons and neutrinos. So the fluxes of the TeV photons and the Fermi accelerated high energy protons \( F_p \), are related through,

\[
F_p(E_p) \approx 5 \times 3 \frac{1}{\Gamma(E_p)} F_{\gamma}(E_{\gamma}),
\]

where the factor 5 corresponds to \( \approx 20\% \) of the proton energy taken by each pion \( \text{(Waxman & Bahcall 1997)} \) and 3/2 is due to the 2/3 probability of \( \Delta \)-resonance decaying to \( p\pi^0 \). The \( \gamma \)-ray flux from photo-hadronic interactions is shown in Fig. 3. We used \( \alpha = 2 \) below 1 TeV and \( \alpha = 2.5 \) above 1 TeV in Eq. (9).

### 3.1 \( \gamma - \gamma \) opacities in emission zones

The accelerated protons in the jet of Cen A, interacts with the target photons available in zone 1 primarily and negligibly in zone 2. Before escaping their respective zones, VHE photons interact with the SSC target radiation field. For head on collision, the pair production condition is \( E'_p, E'_\gamma \geq 2(m_e^2c^2)^2 \). We estimate the opacities of zone 1 and zone 2 using delta function approximation for the \( \gamma - \gamma \) cross section. In this approximation the \( \gamma - \gamma \) opacity in the

| Physical parameters            | Leptonic/lepto-hadronic (zone 1) | Leptonic (zone 2a) | Leptonic (zone 2b) |
|--------------------------------|----------------------------------|--------------------|--------------------|
| Magnetic field \( (B) \)        | 2.5 G                            | 0.02 G             | 0.02 G             |
| Blob radius \( (R_b) \)         | \( 7 \times 10^{15} \) cm        | \( 9.2 \times 10^{15} \) cm | \( 9.2 \times 10^{15} \) cm |
| Lorentz boost factor \( (\Gamma) \) | 7.0                              | 2.0                | 2.0                |
| Angle between jet and l.o.s. \( (\theta_{obl}) \) | \( 30^\circ \)                  | \( 30^\circ \)     | \( 30^\circ \)     |
| Doppler factor \( (\delta_D) \) | 1.0                              | 2.0                | 2.0                |

**Electron spectrum:**

\( (E_{e,\min}, E_{e,br}, E_{e,max}) \)

\( (p_1, p_2) \)

Jet-frame energy density of electrons \( (\text{erg/cm}^3) \)

Emitting blob location along the jet axis

\( 3030 \times R_b \)

**Proton spectrum:**

\( (E_{p,\min}, E_{p,br}, E_{p,max}) \)

\( (\alpha_1, \alpha_2) \)

\( (1, 10^9, 10^{11}) \) GeV

\( (2.0, 2.5) \)

Table 1. Parameters used for the leptonic and hadronic modelling of Cen A. The Schwarzschild radius \( R_s \) for Cen A with black hole mass of \( 5.5 \times 10^7 M_\odot \) is \( 1.65 \times 10^{13} \) cm. Zone 1 is for SSC or SSC+photo-hadronic emission, respectively, in the leptonic or lepto-hadronic case. Zones 2a and 2b represents EC scenario in leptonic and lepto-hadronic cases, respectively.

Figure 1. The SED of Cen A, in two zone leptonic scenario. The data points from radio to GeV energy are taken from \( \text{(Abdo et al. 2010)} \) and references therein. The recent HESS observational data in 213 hours and Fermi-LAT data in 8 years have been used in this plot \( \text{(HESS Collaboration 2017)} \). The fluxes from zone 1 are dominant in synchrotron and SSC emission. The zone 2 emission dominates in the VHE energy range and fits the Fermi-GeV hardness as well as the HESS data. The emission mechanism in zone 2 is EC. The parameters of this model are shown in Table 1. The excess radio emission compared to the model is likely due to a larger radio-emitting region than the jet structure we have used. In general, the blob scenario of AGNs underpredict radio data \( \text{(Krawczynski et al. 2004; Abdo et al. 2010; Petropoulou et al. 2014)} \).
An opacity effect may occur in the broad-line region (BLR) of Cen A, where target photons at infrared wavelengths (0.337-3.37 μm) can be explored to get some constraints from Auger’s observations. If $N$ is the number of events discovered by the PAO then we can write:

$$N = \frac{\Xi \omega(\delta_b) N_0 E_0}{\Omega \delta_b (\alpha - 1)} \left( \frac{E_{th}}{E_0} \right)^{-\alpha}$$

(11)

where $E_{th} = 55$ EeV is the threshold energy of cosmic rays for detection at PAO $\{Aab \ et al. 2015\}$. The cosmic ray spectrum for $N$ cosmic ray events,

$$\frac{dN_p}{dE_p} = 1.2 \times 10^{-4} N(\alpha - 1) \left( \frac{E_{th}}{E_0} \right)^{\alpha - 1} \left( \frac{E_p}{E_0} \right)^{-\alpha}$$

(12)

Using the 13 event data set for Cen A $\{Aab \ et al. 2015\}$ we calculate the spectral index to be $2.55 \pm 0.2$ with reduced $\chi^2=0.7$ for 3 degrees of freedom. We also fit the HESS $\gamma$-ray observation of Cen A using the photo-hadronic model and the spectral index was taken as $2.5$ above $1$ TeV. The peak luminosity in cosmic rays at $1$ TeV to explain HESS observations is $\approx 2.5 \times 10^{36}$ erg/s. The bolometric luminosity for cosmic ray protons in the range $100$ GeV-$100$ EeV is approximately $10^{37}$ erg/s, which is an order of magnitude higher than $L_{Edd}$. Such super-Eddington luminosity is often required for blazar cosmic-ray emission $\{Razzano \ et al. 2012\}$. For $10$ UHECR events above $55$ EeV the luminosity is $1.6 \times 10^{39}$ erg/s, while the total luminosity in cosmic rays above $55$ EeV is approximately $10^{42}$ erg/s for the spectrum required to explain VHE $\gamma$-ray data.

Cosmic rays emitted from Cen A will go through magnetic deflection in the Galactic and intergalactic magnetic field. In the intergalactic medium the deflection can be neglected while in the Galactic case if an UHECR event of energy $E$ enters our Galaxy at latitude $b$ then its deflection $\delta_{\text{diff, MW}}$ in the magnetic field $(B)$ of our Galaxy can be estimated using $\{Dermer \ & Menon 2009\}$:

$$\delta_{\text{diff, MW}} \lesssim \frac{1}{2} \frac{h_{\text{had}}}{\sin(b(E/60EeV))}$$

(13)

Where $h_{\text{had}}$ is the height of the Galactic disk. If we assume, the emitted cosmic ray composition favours cosmic ray protons then their deflection in the Galactic field can be assumed within $1^\circ$. The deflection in the intergalactic medium is negligible for the distance of Cen A $\{Dermer \ & Menon 2009\}$.

5 SUMMARY AND DISCUSSION

The SSC model parameters $\Gamma$, $\theta_{\text{obs}}$, $\delta_D$ used in our model for zone 1, are the same as used in $\{Abdo \ et al. 2014\}$, while we change the magnetic field $B$ and the blob size $R_b$. The parameters of these two models are shown in Table 1. We show that VHE $\gamma$-ray emission gets attenuated severely in zone 1 of Cen A for $\delta_D = 1.0$, which was neglected in earlier works $\{Sahu \ et al. 2012, Joshi \ & Gupta 2013\}$. One zone photo-hadronic model has been discussed for $\delta_D = 1.0$, which explains the GeV hardness and $\delta_D = 2.0$, which allows VHE $\gamma$-ray to escape from Cen A $\{Petropoulou \ et al. 2014\}$. In this work, we consider $\delta_D = 1.0$ case, where VHE $\gamma$-ray attenuation in zone 1 are calculated to explain SED of Cen A in two zone pure leptonic model and lepto-hadronic model. The GeV hardness in our model has been addressed using a second zone with $\delta_D = 2.0$ where the EC process is effective.

We find that both pure leptonic and lepto-hadronic scenarios in our two-zone model can satisfactorily explain the SED of Cen A. The association of UHECR events with Cen A naturally brings into question of electromagnetic signature of these energetic particles. In our lepto-hadronic model, protons with the same spectral shape
by fitting UHECR data from Cen A (Aab et al. 2015) can account for observed VHE $\gamma$-ray emission through photo-hadronic interactions. The luminosity in protons above 55 EeV is $10^{12}$ erg/s for the spectrum required to fit VHE $\gamma$-ray data. This is roughly a factor $6 \times 10^2$ higher than the luminosity in UHECRs from Cen A above 55 EeV. This factor could arise from the fact that the jet of Cen A is $30^\circ$ off axis from our line of sight and only a fraction of the particles in the jet can reach us, which are significantly deflected by the magnetic field in the large-scale jet and lobes to our line of sight (Dermer et al. 2009).

Cen A, the nearest radio galaxy, is a test bed for applying our knowledge of particle acceleration to ultrahigh energies, study and model their interactions to interpret data. It will continue to be an intriguing source in foreseeable future.

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Figure 3. The SED of Cen A, in two zone leptonic and photo-hadronic scenario. The SSC emission from zone 1 is similar to the pure leptonic model in Fig. 1. We calculate the VHE $\gamma$-ray flux using the photo-hadronic interaction in zone 1. The attenuation impacts on these photons due to zone 1 target photons (see Fig. 2) suppress the VHE spectrum. Here the emission from zone 2 in the EC scenario has been tuned to produce the GeV hardness observed in the spectrum of Cen A.
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