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CORRELATION OF $\gamma$-RAY AND HIGH-ENERGY COSMIC RAY FLUXES FROM THE GIANT LOBES OF CENTAURUS A

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ABSTRACT

The spectral energy distribution of giant lobes shows one main peak detected by the Wilkinson Microwave Anisotropy Probe at the low energy of $10^{-5}$ eV and a faint $\gamma$-ray flux imaged by the Fermi Large Area Telescope at an energy of $\geq 100$ MeV. On the other hand, the Pierre Auger Observatory associated some ultra-high-energy cosmic rays with the direction of Centaurus A and IceCube reported 28 neutrino-induced events in a TeV–PeV energy range, although none of them related with this direction. In this work, we describe the spectra for each of the lobes, the main peak with synchrotron radiation, and the high-energy emission with $p$–$p$ interactions. After obtaining a good description of the main peak, we deduce the magnetic fields, electron densities, and the age of the lobes. Successfully describing the $\gamma$-ray emission by $p$–$p$ interactions and considering thermal particles in the lobes with density in the range $10^{-10}$–$10^{-4}$ cm$^{-3}$ as targets, we calculate the number of ultra-high-energy cosmic rays. Although the $\gamma$-spectrum is well described with any density in the range, only when $10^{-3}$ cm$^{-3}$ is considered are the expected number of events very similar to that observed by the Pierre Auger Observatory, otherwise we obtain an excessive luminosity. In addition, correlating the $\gamma$-ray and neutrino fluxes through $p$–$p$ interactions, we calculate the number of high-energy neutrinos expected in IceCube. Our analysis indicates that neutrinos above 1 TeV cannot be produced in the lobes of Centaurus A, which is consistent with the results recently published by the IceCube Collaboration.

Key words: acceleration of particles – galaxies: active – galaxies: individual (Centaurus A) – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Centaurus A (Cen A), at a distance of 3.8 Mpc, is the nearest radio-loud, active galactic nucleus (AGN). Due to its distance, Cen A is an excellent source for studying the physics of relativistic outflows and radio lobes. It has a jet with an axis subtending an angle to the line of sight estimated as 15°–80° (see, e.g., Horiiuchi et al. 2006 and references therein) and two giant lobes oriented primarily in the north–south direction, which subtend $\sim 10^\circ$ on the sky. They were imaged and analyzed by the Parkes radio telescope at 6.3 cm (Junek et al. 1993; Alvarez et al. 2000) and at 22, 33, 41, 61, and 94 GHz by the Wilkinson Microwave Anisotropy Probe (WMAP; Hinshaw et al. 2009; Page et al. 2003; Hardcastle et al. 2009; Abdo et al. 2010a). Also, for a period of 10 months, Cen A was monitored by the Large Area Telescope (LAT) on board the Fermi Gamma-Ray Space Telescope (Atwood et al. 2009), and $\gamma$-ray excesses were detected from both lobes. The resulting LAT image showed the $\gamma$-ray peak coincident with the AGN detected by the Compton/EGRET instrument (Hartman et al. 1999). Assuming a power law for the $\gamma$-ray spectra and from the resultant test statistics (Mattox et al. 1996), LAT recorded a flux of $(0.77 \pm 0.23 / -0.19)_{\text{stat}} (\pm 0.39)_{\text{sys}} \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$ with a photon index of $2.52 \pm 0.16 / -0.19$ for the north lobe and a flux of $(1.09 \pm 0.24 / -0.21)_{\text{stat}} (\pm 0.32)_{\text{sys}} \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$ with a photon index of $2.60 \pm 0.14 / -0.15$ for the south lobe (Abdo et al. 2010a).

Hardcastle et al. (2006) have claimed that the oncoming jet enters the northern inner lobe, encrusted in the thermal interstellar gas of NGC 5128, at $\sim 3.5$ kpc. Based on deep Chandra observations, Hardcastle et al. (2007) retracted that the receding jet extends out to $\sim 2.5$ kpc in protection in X-rays, also showing up on a similar scale in radio (Hardcastle et al. 2003; Tingay et al. 1998). Based on the detection of extended thermal X-ray emission from this region, Kraft et al. (2009) interpreted the northern middle lobe as an old structure that has recently become reconnected to the energy supply from the jet (Wykes et al. 2013).

Based on X-ray (0.5–2.5 keV) measurements and supposing that all of the emission comes from a uniform thermal plasma, Hardcastle et al. (2009) established a strict upper limit on this plasma, that is $n_p \sim 10^{-3}$ cm$^{-3}$. Recently, considering the internal Faraday rotation scenario, O’Sullivan et al. (2013) presented a positive detection of the internal depolarization signal leading to the same value of density. Also, Stawarz et al. (2013) presented an analysis of the diffuse X-ray emission and found a tentative detection of a soft excess component with an energy of $kT \sim 0.5$ keV, corresponding to the same value of the number density of the thermal gas. However, Wykes et al. (2013) estimated the values of total entrainment, buoyancy age, and the average volume of the giant lobes and found a different number density of thermal particles, $n_p \sim 10^{-9}$ cm$^{-3}$. In addition, they calculated that the relativistic electron number densities for four giant lobe sectors defined by Hardcastle et al. (2009) were in the range $1.0 \times 10^{-11}$ cm$^{-3} \leq N_e \leq 1.5 \times 10^{-8}$ cm$^{-3}$.

Otherwise, based on the report given by the Pierre Auger Collaboration (PAO) with respect to the anisotropy in the arrival direction of ultra-high-energy cosmic rays (UHECRs; Pierre Auger Collaboration et al. 2007, 2008) and the possible correlation with Cen A, some authors have pointed out that Cen A has the potential to accelerate protons up to UHEs (e.g., Gorbunov et al. 2008; Moskalenko et al. 2009; Dermer et al. 2009; Romero et al. 1996; Fraija et al. 2012a).

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Recently, IceCube reported the detection of events in an energy range of TeV–PeV (IceCube Collaboration et al. 2013a, 2013b), and although these events have been discussed to have an extragalactic origin (Cholis & Hooper 2013; Liu & Wang 2013; Murase & Ioka 2013; Razzaque 2013; Fraija 2014), they were not correlated with the direction of Cen A.

On the other hand, although energy ranges in radio, infrared, optical (Winkler & White 1975; Mushotzky et al. 1976; Bowyer et al. 1979; Bailey et al. 1981; Combi & Romero 1997), X-ray, and γ-rays (MeV–TeV; Abdo et al. 2010b; Sreekumar et al. 1999; Aharonian et al. 2009) have been detected close to the core of Cen A, only photons in radio and γ-rays have been collected from the lobes; and the spectral energy distribution (SED) of each lobe has been described with leptonic models, radio (WMAP) data through synchrotron radiation and Fermi-LAT data through inverse-Compton (IC)-scattered radiation from the cosmic microwave background (CMB; Crusius & Schlickeiser 1986; Blumenthal & Gould 1970) and extragalactic background light (EBL; Abdo et al. 2010a; Hardcastle et al. 2009; Yang et al. 2012; Hauser & Dwek 2001; Georganopoulos et al. 1970; Baity et al. 1981; Combi & Romero 1997), X-ray, γ-rays have been measured by WMAP (Hinshaw et al. 2013; Murase & Ioka 2013; Razzaque 2013; Fraija 2014), they were not correlated with the direction of Cen A.

The non-thermal radio emission can be inferred through synchrotron radiation generated by an electron distribution. The population of these accelerated electrons can be described by a BPL, given by (Longair 1994; Hardcastle et al. 2001, 2006; Hardcastle & Croston 2011)

\[ N_e(\gamma_e) = A_e \left\{ \begin{array}{ll} \frac{\alpha}{\gamma_e} & \gamma_e < \gamma_{e,b}, \\
\frac{\gamma_{e,b}}{\gamma_{e,b} - \gamma_{e,m}} & \gamma_{e,b} \leq \gamma_e < \gamma_{e,max}. \end{array} \right. \]

where \( A_e \) is the proportionality electron constant, \( \alpha \) is the spectral index, and \( \gamma_{e,i} \) are the electron Lorentz factors. The index \( i \) is \( m \), \( b \), or \( max \) for minimum, break, and maximum, respectively. Assuming an equipartition of energy density between magnetic field \( B = B^2 / 8\pi \) and electrons \( U_e = m_e \int \gamma_e N_e(\gamma_e) d\gamma_e \), the electron Lorentz factors are

\[ \gamma_{e,m} = \frac{(\alpha - 2) U_e}{m_e (\alpha - 1) N_e}, \]
\[ \gamma_{e,b} = \frac{3 m_e}{4 \alpha T \beta^2} U_B^{-1} t_{syn}^{-1}, \]
\[ \gamma_{e,max} = \left( \frac{9 q_e^2}{8 \pi \sigma_T \beta^4} \right)^{1/4} U_B^{-1/4}, \]

where the constants \( m_p, m_e, q_e, \) and \( \sigma_T \) are the proton mass, electron mass, electric charge, and Thomson cross section, respectively, \( \beta = v/c \sim 1 \) and \( z = 0.00183 \) is the redshift (Israel 1998). The observed photon energies,

\[ \epsilon_{\gamma,obs}(\gamma_e) = \sqrt{(8\pi q_e^2/m_e^2)(1+z)^{-1} \delta_D U_B^{1/2} \gamma_{e,i}}, \]

for each Lorentz factor (Equation (2)) are

\[ \epsilon_{\gamma,m}^{obs} = \frac{\sqrt{8\pi q_e^2}}{m_e (\alpha - 1)^2} (1+z)^{-1} \delta_D U_B^{1/2} U_e^{2} N_e^{-2}, \]
\[ \epsilon_{\gamma,c}^{obs} = \frac{9 q_e}{8 \sigma_T \beta^4} (1+z)^{-1} \delta_D U_B^{-3/2} N_e^{-2}, \]
\[ \epsilon_{\gamma,max}^{obs} = \frac{3 q_e}{m_e \sigma_T \beta^2} (1+z)^{-1} \delta_D, \]

where we have applied the synchrotron cooling timescale,

\[ t_{syn} = \frac{E_e'}{(dE_e/dt)} = \frac{3 m_e}{4 \alpha T \beta^2} U_B^{-1} \epsilon_{\gamma}^{2}, \]

and \( d_D \) is the Doppler factor. On the other hand, the synchrotron spectrum is obtained by the shape of the electron spectrum (Equation (1)) rather than the emission spectrum of a single particle. Therefore, the energy radiated in the range \( \gamma_e \) to \( \gamma_e + d\gamma_e \) is given by electrons between \( E_e \) and \( E_e + dE_e \), then, we can estimate the photon spectrum through emissivity \( \epsilon_{\gamma} N_{\gamma}(\epsilon_{\gamma}) d\epsilon_{\gamma} = (dE_e/dt) N_{\gamma}(E_e) dE_e \). Following Longair (1994) and Rybicki & Lightman (1986), it is easy to show that if electron distribution has spectral indices \( \alpha \) and \( \alpha - 1 \), then the photon distribution has spectral indices \( p = (\alpha - 1)/2 \) and \( p = \alpha/2 \), respectively. The proportionality constant is estimated by calculating the total number of radiating electrons in the actual volume, \( n_e = N_e / V = 4\pi N_e r_d^{3}/3 \), the maximum radiation power \( P_{\gamma,max}^{obs} \simeq (dE_e/dt)/(\epsilon_{\gamma}(\gamma_e)) \), and the distance \( D_z \) from the source. Then, we can obtain the observed synchrotron spectrum as follows:

\[ \epsilon_{\gamma}^{2} N_{\gamma}(\epsilon_{\gamma}) = \begin{cases} 
\epsilon_{\gamma,m}^{obs} & \epsilon_{\gamma}^{obs} < \epsilon_{\gamma,m}, \\
\epsilon_{\gamma,c}^{obs} & \epsilon_{\gamma}^{obs} < \epsilon_{\gamma,c}, \\
\epsilon_{\gamma,max}^{obs} & \epsilon_{\gamma}^{obs} < \epsilon_{\gamma,max}, 
\end{cases} \]

(5)
where
\[ A_{\text{syn}, \gamma} = \frac{p_{\gamma, \max}^{\text{obs}} n_x}{4\pi m_\gamma} e_{\gamma, m} \]
\[ \simeq \frac{8\pi \sigma_T \beta^2 (\alpha - 2)^2}{9 m_\gamma^2 (\alpha - 1)^2} D_\gamma^2 U_B u_\gamma^2 N_e r_d^2. \] (6)

It is important to clarify that \( r_d \) is the region where emitting electrons are confined. Equation (5) represents the peak at lower energies (radio wavelength) of the SED for each of the lobes.

### 2.2. Proton–Proton Interactions

We suppose that accelerated protons are cooled down through \( p-p \) interactions (Becker 2008; Atoyan & Dermer 2003; Dermer & Menon 2009; Aharonian 2002). Proton–proton interactions are given mainly through

\[ p + p \rightarrow \pi^\pm + \pi^- + \pi^0 + X. \] (7)

Taking into account that neutral pions decay in two gammas, \( \pi^0 \rightarrow \gamma \gamma \), and the minimum energy of photo-pion, \( E_{\pi, \text{min}} \), at rest frame is \( m_\pi = 139.57 \text{ MeV} \), then the minimum observed energy is

\[ \epsilon_{\gamma, \pi^0, \text{min}} \simeq \frac{\delta_D}{(1 + z)} m_\pi^0. \] (8)

Also, charged pions decay in neutrinos as follows:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\tau, \] (9)

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \nu_e + \nu_\mu + \bar{\nu}_\tau, \] (10)

hence neutrino flux is expected to be accompanied by a \( \gamma \)-ray flux.

Assuming that accelerated protons interact with thermal particles whose number density lies in the range \( 10^{-10} \text{ cm}^{-3} \leq n_p \leq 10^{-4} \text{ cm}^{-3} \) (Hardcastle et al. 2009; O’Sullivan et al. 2013; Wykes et al. 2013; Stawarz et al. 2013), then the \( \gamma \)-ray spectrum, \( dN_\gamma / dE_{\gamma, \pi^0} \), produced by \( p-p \) interactions is (Atoyan & Dermer 2003; Fraija et al. 2012a; Aharonian 2002; Hardcastle et al. 2009)

\[ f_{\gamma, pp}(E_\gamma) E_\gamma \frac{dN_p}{dE_p} \frac{d}{dE_p} E_p = \epsilon_{\gamma, \pi^0}(E_\gamma) \frac{dN_p}{dE_p}, \] (11)

where \( f_{\gamma, pp} \approx \tau_{\text{obs}} / t_{\text{pp}} = \tau_{\text{obs}} n_p k_{\text{pp}} \sigma_{\text{pp}} \) is the fractional power released, \( \sigma_{\text{pp}} \approx 0.095 + 0.06 \ln(E/\text{GeV}) \) mb is the nuclear interaction cross section, \( k_{\text{pp}} = 1/2 \) is the inelasticity coefficient, \( n_p \) is the thermal particle density, \( t_{\text{obs}} \) is the age of the lobe, and \( t_{\text{pp}} \) is the characteristic cooling time for this process.

Taking into account that a pion carries 33% of the proton energy \( (\xi = 0.33) \) and supposing that \( \gamma \)-ray spectrum at GeV energy range is produced by a simple proton power law,

\[ \left( \frac{dN_p}{dE_p} \right)^{\text{obs}} = A_p \left( \frac{E_p}{\text{GeV}} \right)^{-\alpha}, \] (12)

where \( A_p \) is the proportionality constant normalized to GeV and \( \alpha \) is the spectral index, then the observed \( \gamma \)-ray spectrum is

\[ \left( \frac{\epsilon_{\gamma} dN_\gamma}{dE_\gamma} \right)^{\text{obs}} = A_{\gamma, pp} \left( \frac{E_{\gamma, \pi^0}}{\text{GeV}} \right)^{2-\alpha}, \] (13)

where \( A_{\gamma, pp} = f_{\gamma, pp} (2/\xi)^2 A_p \text{ GeV}^2 \) and the proton luminosity, \( L_p \approx 4\pi F_p = 4\pi \int E_p (dN_p / dE_p) dE_p \), can be written as

\[ L_p = \frac{4\pi (\xi/2)^{2-\alpha}}{(\alpha - 2)} D_\gamma^2 f_{\gamma, pp} A_{\gamma, pp} \left( \frac{E_{\gamma, \pi^0}}{\text{GeV}} \right)^{2-\alpha}. \] (15)

where \( E_{\gamma, \text{min}} \) corresponds to the proton energy at GeV energies. Equation (13) shows the contribution of \( p-p \) interactions to the \( \gamma \)-ray spectrum for each of the lobes.

### 3. PRODUCTION OF ULTRA-HIGH-ENERGY COSMIC RAYS

It has been proposed that astrophysical sources accelerating UHECRs could produce HE \( \gamma \)-rays and neutrinos by proton interactions with photons at the source and/or the surrounding radiation and matter. We propose that the spectrum of accelerated protons is extended from GeV to \( \sim 10^{20} \) eV energies and can also be determined through the signature (\( \gamma \)-ray flux) produced at GeV energies. This \( \gamma \)-ray flux is correlated with proton flux through Equation (14). In addition, we correlate the \( \gamma \)-ray and neutrino fluxes to find the parameters of the neutrino spectrum (Becker 2008). Based on these correlations, we are going to calculate the number of events for these spectra at energy ranges of PAO and IceCube.

### 3.1. UHE Protons

PAO, studying the composition of the HE showers, found that the distribution of their properties was situated somewhere between pure \( p \) and pure \( Fe \) at 57 GeV (Yamamoto 2008; Pierre Auger Collaboration et al. 2008; Unger et al. 2007). By contrast, High Resolution Fly’s Eye cosmic-ray detector data are consistent with a dominant proton composition at these energies but uncertainties in the shower properties (Unger et al. 2007) and in the particle physics extrapolated to this energy scale (Engel 2008) preclude definitive statements about the composition. At least two events of the UHECRs observed by PAO were detected (Pierre Auger Collaboration et al. 2007, 2008) inside a 3:1 circle centered at Cen A.

#### 3.1.1. Mechanisms of UHECR Acceleration

The maximum energy required for acceleration of UHECRs is limited by both the size (\( R \)) and magnetic field (\( B \)) of the emission region, \( E_{\text{max}} = \text{ZeB} \Gamma \) (Hillas 1984). Additional limitations are mainly due to radiative losses or available time when particles diffuse through the magnetized region. In Cen A, a short distance \( (\sim 10^{15} \text{ cm}) \) from the black hole (BH), the emission region is limited by the variability timescale \( R = r_d = (c \Delta D / (1 + z)^2) dt_{\text{obs}} \), hence the maximum energy required is (Abdo et al. 2010b; Sahu et al. 2012)

\[ E_{\text{max}} = 4 \times 10^{19} \text{ eV} B_{0.8} d_{\text{obs}} \Gamma_{0.85}. \] (16)

At a 100 kpc distance from the BH, particles are accelerated inside the lobes, therefore the emission region is limited by the size of the lobes, and the maximum energy is

\[ E_{\text{max}} = \text{ZeB} \Gamma \]. \] (17)

with \( R = 100 \text{ kpc} \) corresponding to a volume of \( V = 1.23 \times 10^{41} \text{ cm}^{-3} \) and \( B \) is the magnetic field of lobes. The
acceleration and diffuse timescales are
\[ t_{\text{acc}} \simeq 2\pi \frac{E_{\text{max}}}{eB} \] (18)
and
\[ t_{\text{diff}} \simeq \frac{3}{2\pi} \frac{R^2 eB}{E_{\text{max}}}, \] (19)
respectively. As the lobes are inflated by jets in the surrounding medium, accelerated protons are injected inside by the jet, and confined within the lobes, by means of resonant Fermi-type processes (Hardcastle et al. 2009). The non-thermal and the upper limit thermal pressure in the lobes are \( p_{\text{th}} \simeq (U_e + U_B + U_p) \) and \( p_{\text{th}} = n_p K T \), respectively, where \( U_p \sim 2 L_p t_{\text{lobe}}/V \) is the energy density of accelerated proton, \( k \) is the Boltzmann constant, and \( T \) is the temperature. Assuming an equipartition between magnetic field and relativistic electron, \( U_e = \lambda_{e,B} U_B \), then the non-thermal pressure and the total energy can be written as
\[ p_{\text{th}} \simeq U_B(1 + \lambda_{e,B}) + 2 L_p t_{\text{lobe}}/V \] (20)
and
\[ E_{\text{tot}} \simeq U_B V(1 + \lambda_{e,B}) + 2 L_p t_{\text{lobe}}, \] (21)
respectively. As one can observe from the values of the emission region in the jet (Equation (16)), protons may or may not be accelerated up to energies above 40 EeV, depending on the variability timescale and strength of the magnetic field. Hence, it is important to mention that protons could have a hybrid acceleration mechanism, partially in the jet and finally in the lobes.

On the other hand, supposing that the BH jet has the power to accelerate particles up to UHEs through Fermi processes, then from the equipartition magnetic field \( \epsilon_B \) and during flaring intervals for which the apparent isotropic luminosity can reach \( \approx 10^{45} \text{erg s}^{-1} \), one can derive the maximum particle energy of accelerated UHECRs as (Dermer et al. 2009; Fraija et al. 2012a)
\[ E_{\text{max}} \approx 1 \times 10^{20} \frac{Z e \sqrt{\epsilon_B L / 10^{45}}} {\phi \beta^{3/2} \Gamma} \text{eV}, \] (22)
where \( \Gamma = 1/\sqrt{1 - \beta^2}, \phi \simeq 1 \) is the acceleration efficiency factor and \( Z \) is the atomic number.

Other more exotic mechanisms that have been described in the literature are magnetic reconnection and stochastically acceleration by temperatures. In the magnetic reconnection framework, the free energy stored in the helical configuration can be converted to particle kinetic energy in the region where the un-reconnected (upstream) magnetized fluid converges into the reconnection layer, resulting in a continuously charged particle acceleration. Some authors (Birk & Lesch 2000; Giannios 2010; Wykes et al. 2013) have proposed that this mechanism might accelerate UHECRs either in the jet or in the giant lobes. Recently, Wykes et al. (2013) proposed that UHECRs could be stochastically accelerated by high temperatures, being responsible for the self-consistency between the entrainment calculations and the missing pressure in the lobes.

3.1.2. The Expected Number of UHECR

To determine the number of UHECRs, we take into account the PAO exposure, which for a point source is given by \( \Xi_{\text{top}} \omega(\delta) / \Omega_{60} \), where \( \Xi_{\text{top}} = (15/4) \times 10^3 \text{km}^2 \text{yr} \) and 60 is the total operational time (from 2004 January 1 until 2007 August 31), \( \omega(\delta) \simeq 0.64 \) is an exposure correction factor for the declination of Cen A, and \( \Omega_{60} \simeq \pi \) is the Auger acceptance solid angle (Cuoco & Hannestad 2008). The expected number of UHECRs for each of the lobes of Cen A observed above an energy of 60 EeV is given by
\[ N_{\text{UHECR}} = (\text{PAO Expos.}) \times N_p, \] (23)
where \( N_p \) is calculated from a simple and BPL of the proton spectrum at energies higher than 60 EeV. In the first case, considering a simple power law, Equation (12) and from Equations (14) and (23), the expected number of UHECRs is
\[ N_{\text{UHECR}} = \frac{\Xi_{\text{top}} \omega(\delta) (\xi/2)^{2-a}} {\Omega_{60} (\alpha - 1)} \times \int_{\pi_0}^{\pi} f_{n_0,pp} A_{pp,y} \left( \frac{60 \text{EeV}} {\text{GeV}} \right)^{-\alpha+2} \text{EeV}^{-1}. \] (24)
that corresponds to an isotropic UHECR luminosity (Dermer et al. 2009)
\[ L_{\text{UHECR}} = \frac{4 \pi (\xi/2)^{2-a}} {\pi \alpha - 2 D_f^{1/2} A_{pp,y} \left( \frac{60 \text{EeV}} {\text{GeV}} \right)^{2-a}} \] (25)
In the second case, we assume that the proton spectrum is not extended continually up to \( \sim 10^{20} \), but broken at some energy less than 60 EeV. Hence, it can be written as
\[ \frac{dN_p}{dE_p} = A_p \left[ \left( \frac{E_p}{\text{GeV}} \right)^{-\alpha} \right] E_p < E_p,b \] (26)
where \( \beta \) and \( E_p,b \) are the higher spectral index and break proton energy, respectively. In this case, the number of expected events is
\[ N_{\text{UHECR}} = \frac{\Xi_{\text{top}} \omega(\delta) \xi/2^{2-a}} {\Omega_{60} (\alpha - 1)} \times \int_{\pi_0}^{\pi} f_{n_0,pp} A_{pp,y} \left( \frac{E_p}{\text{GeV}} \right)^{-\alpha+\beta} \left( \frac{E_p,b}{\text{GeV}} \right)^{-\beta} \text{EeV}^{-1}, \] (27)
where in Equation (27) \( \beta \) and \( E_p,b \) are the unknown quantities.

3.2. High-energy Neutrinos

Neutrinos are detected when they interact inside the instrumented volume. The path length, \( L(\theta) \), traversed within the detector volume by a neutrino with zenith angle, \( \theta \), is determined by the detector’s geometry. At first approximation, neutrinos are detected if they interact within the detector volume, i.e., within the instrumented distance \( L(\theta) \). The probability of interaction for a neutrino with energy \( E_\nu \) is
\[ P(E_\nu) = 1 - \exp \left[ -\frac{L}{\lambda_{\nu}(E_\nu)} \right] \sim \frac{L}{\lambda_{\nu}(E_\nu)}, \] (28)
where the mean free path in ice is
\[ \lambda_{\nu}(E_\nu) = \frac{1} {\rho_{\text{ice}} N_A \sigma_{\nu N}(E_\nu)}. \] (29)
Here, $\rho_{\text{ice}} = 0.9$ g cm$^{-3}$ is the density of the ice, and $N_A = 6.022 \times 10^{23}$ g$^{-1}$ and $\sigma_{\nu N}$ is the neutrino–nucleon cross section. A neutrino flux, $dN_\nu/dE_\nu$, crossing a detector with energy threshold $E_{\text{th}}$ and cross-sectional area $A(E_\nu, \theta)$ facing the incident beam will produce

$$N_\nu = \int_{E_{\text{th}}}^{\infty} A(E_\nu) \frac{dN_\nu}{dE_\nu} dE_\nu$$

(30)
events after a time, $T$. Furthermore, the “effective” detector area, $A(E_\nu, \theta)$, is clearly also a function of zenith angle, $\theta$. In practice, $A(E_\nu, \theta)$ is determined as a function of the incident neutrino direction and zenith angle by a full-detector simulation including the trigger. It is of the order of 1 km$^2$ for IceCube, so the effective volume for showers is $V_{\text{eff}} \approx A(E_\nu, \theta) L(\theta) \approx 2$ km$^3$. Finally, the expected event rate is

$$N_{\nu_e} \approx T \rho_{\text{ice}} N_A V_{\text{eff}} \int_{E_{\text{th}}}^{\infty} \sigma_{\nu N}(E_\nu) \frac{dN_\nu}{dE_\nu} dE_\nu,$$

(31)

where $E_{\text{th}}$ is the threshold energy, and $\sigma_{\nu N}(E_\nu) = 5.53 \times 10^{-36} (E_\nu$/GeV$)^{3.63}$ cm$^2$ is the charged current cross section (Gandhi et al. 1998).

Proposing that the neutrino spectrum can be written as

$$\frac{dN_\nu}{dE_\nu} = A_\nu \left( \frac{E_\nu}{\text{GeV}} \right)^{-\alpha_\nu},$$

(32)

where the normalization factor, $A_\nu$, is calculated by correlating the neutrino flux luminosity with the GeV photon flux (Becker 2008). This correlation is given by

$$\int \frac{dN_\nu}{dE_\nu} E_\nu dE_\nu = \int \frac{dN_\gamma}{dE_\gamma} E_\gamma dE_\gamma.$$ 

(33)

Here, we have used $K = 1$ for $p-p$ interactions (see, e.g., Halzen 2007 and references therein). Assuming that the spectral indices for neutrino and $\gamma$-ray spectrum are similar $\alpha \simeq \alpha_\nu$ (Becker 2008), and taking into account that each neutrino carries 5% of the proton energies ($E_\nu = 1/20 E_p$) and each photon carries 16.7% of proton energy (Halzen 2013), then the normalization factors are related by

$$A_\nu = A_{pp,\gamma} (10 \xi)^{-\alpha+2} \text{GeV}^{-2},$$

(34)

where $A_{pp,\gamma}$ is given by Equation (14).

If we assume that the neutrino spectrum extends continually over the whole energy range (Cuoco & Hannestad 2008), then the expected number of neutrinos is

$$N_{\nu_e} \approx T \rho_{\text{ice}} N_A V_{\text{eff}} \int_{E_{\text{th}}}^{\infty} \frac{dN_\nu}{dE_\nu} \frac{E_\nu^{\alpha_\nu+1}}{\text{GeV}^{-\alpha_\nu+1.63}} \text{GeV}^{-1},$$

(35)

and if it is broken at energy $E_{\nu,b} = (1/20)E_{p,b}$, then

$$\frac{dN_\nu}{dE_\nu} = A_\nu \left\{ \begin{array}{ll} \left( \frac{E_\nu}{\text{GeV}} \right)^{-\alpha} \quad & \text{for } E_\nu < E_{\nu,b}, \\
\left( \frac{E_{\nu,b}}{\text{GeV}} \right)^{-\alpha+\beta} \left( \frac{E_\nu}{\text{GeV}} \right)^{-\beta} \quad & \text{for } E_{\nu,b} \leq E_\nu. \end{array} \right.$$ 

(36)

For this case, the expected event is

$$N_{\nu_e} \approx T \rho_{\text{ice}} N_A V_{\text{eff}} A_\nu \left( 5.53 \times 10^{-36} \text{ cm}^2 \right)$$

$$\times \left[ \left( \frac{E_{\nu,b}}{\text{GeV}} \right)^{-\alpha+1.63} + \alpha - \beta \left( \frac{E_{\nu,b}}{\text{GeV}} \right)^{-\beta+1.63} \right] \text{GeV}^{-1},$$

(37)

where the higher spectral index, $\beta$, is given by the BPL of proton spectrum.

4. ANALYSIS AND RESULTS

We have developed a synchrotron emission and $p-p$ interaction model to describe the spectra for the north and south lobes of Cen A. In the synchrotron radiation model, we have used an electron distribution described by a BPL (Equation (1)) with the minimum Lorentz factor calculated through electron density and electron energy density (Equation (2)). The synchrotron spectrum obtained (Equation (5)) depends on magnetic and electron energy densities, electron density, size of emission region, and cooling timescale characteristic for this process, through the synchrotron normalization constant (Equation (6)) and break energies (characteristic and cut-off, Equation (3)). Taking into account that the jet extends out to $\sim 3$ kpc in projection in radio (Hardcastle et al. 2007, 2003; Tingay et al. 1998), we consider an emission region scale of this size. Also, we have supposed that the magnetic and electron energy densities are equipartitioned through the parameter $\lambda_{e, B} = U_e/U_B$. In the $p-p$ interaction model, we have considered accelerated protons described by a simple power law (Equation (12)) which could be accelerated in the jet or/and the size of the lobe and furthermore interact with thermal particles in the lobes. The spectrum generated by this process (Equation (13)) depends on the proton luminosity (through $A_p$), number density of thermal particles, age of the lobe, and spectral index. The age of the lobe can be estimated through the cooling timescale of radiating electrons (Hardcastle et al. 2009) and the number density lies in the range $10^{-10}$ cm$^{-3} \leq n_p \leq 10^{-4}$ cm$^{-3}$.

To find the best fit of the set of model parameters with data for each lobe, we use the method of chi-square ($\chi^2$) minimization (Brun & Rademakers 1997). We have fitted WMAP and Fermi data for each of the lobes with synchrotron emission (Equations (3) and (5)) and $p-p$ interaction (Equation (13)), respectively. As shown in Appendix A, we first found the photon spectral index ($\alpha$) and the normalization constant ($A_{pp,\gamma}$) of the $\gamma$-ray spectrum generated by the $p-p$ interaction model. Second, with the fitting spectral index, we fit WMAP data with the synchrotron model to find the break energies (characteristic $E_{\gamma,m}$ and cut-off $E_{\gamma,c}$) and the normalization constant characteristic of this process ($A_{\gamma,m,n}$). Finally, after fitting the SED of each lobe, we plot Figure 1 presenting the best set of these parameters: $p-p$ interaction parameters in Table 1 and synchrotron radiation parameters in Table 2 (see Appendix A).

As shown in Table 1, it can be seen that the values of normalization constant $A_{pp,\gamma}$ and photon spectral index ($\alpha$) of the $\gamma$-ray spectra for each of the lobes are $5.10 \pm 0.96$ erg cm$^{-2}$ s$^{-1}$ (north) and $8.07 \pm 1.58$ erg cm$^{-2}$ s$^{-1}$ (south), and 2.519 (north) and 2.598 (south), respectively, which were first obtained by Abdol et al. (2010a). From the values of the best set of parameters obtained with the synchrotron model (Table 2 and Equations (6) and (3)), we plot the synchrotron cooling time
scale \((t_{\text{syn}})\), the electron density \((N_e)\), and equipartition parameter \((\lambda_{\text{e},B})\) as a function of magnetic field \((B)\), as shown in Figure 2. For the north lobe, considering the value of equipartition parameter \(\lambda_{\text{e},B} = 4.3\) (Abdo et al. 2010a), we found the value of the magnetic field, \(B = 3.41 \mu \text{G}\), and then the values of synchrotron cooling time, \(t_{\text{syn}} = 55.1\) Myr, and electron density, \(N_e = 2.1 \times 10^{10} \text{ cm}^{-3}\). For the south lobe, considering the value of equipartition parameter \(\lambda_{\text{e},B} = 1.8\) (Abdo et al. 2010a), we found the value of the magnetic field, \(B = 6.19 \mu \text{G}\), and then the values of synchrotron cooling time, \(t_{\text{syn}} = 27\) Myr, and electron density, \(N_e = 3.9 \times 10^{10} \text{ cm}^{-3}\).

On the other hand, from the values of the observed quantities and parameters given in Tables 1 and 2, we first analyze the contributions of \(p-\gamma\) interactions and IC scattering of CMB and EBL to the \(\gamma\)-ray spectra and second, from \(p-\gamma\) interactions we correlate the \(\gamma\)-ray, UHECRs, and neutrino fluxes to estimate the number of UHE protons and neutrinos expected in PAO and IceCube, respectively. These estimations are done by assuming that these spectra are extended up to the energy range of each of the experiments.

Relativistic electrons may upscatter synchrotron photons up to higher energies given by

\[
E_{\gamma,k}^{ic} \simeq \frac{\gamma_{e,m}^2}{\gamma_{\gamma,m}} E_{\gamma,k},
\]

where the index \(k\) represents the CMB and EBL photons (Hauser & Dwek 2001; Georganopoulos et al. 2008; Raue & Mazin 2008; Dermer 2013). Taking into account the radiation power typical of this process, \(dE/dt = 4/3 \sigma_T \beta^2 \gamma_{\gamma,k}^2 U_{\gamma,k}\), and performing a process similar to that done with synchrotron emission, the IC spectrum can be written as

\[
\epsilon_{\gamma}^{ic} N_{\gamma}(\epsilon_{\gamma}^{ic}) = A_{ic,\gamma},
\]

\[
\times \left\{ \begin{array}{l}
\frac{\epsilon_{\gamma}^{ic}}{\epsilon_{\gamma,m}^{ic}} \frac{4/3}{(\alpha-3)/2} \\
\frac{\epsilon_{\gamma}^{ic}}{\epsilon_{\gamma,m}^{ic}} \epsilon_{\gamma,m}^{ic} \end{array} \right\} \left( \epsilon_{\gamma}^{ic} \right)^{-(\alpha-2)/2} \left( \epsilon_{\gamma}^{ic}/\epsilon_{\gamma,m}^{ic} \right)^{-(\alpha-3)/2},
\]

where \(\epsilon_{\gamma}^{ic,\text{obs}} < \epsilon_{\gamma,m}^{ic,\text{obs}} < \epsilon_{\gamma,c}^{ic,\text{obs}} < \epsilon_{\gamma,\text{max}}^{ic,\text{obs}}\)...

\[
(39)
\]

Figure 1. Fit of observed SED of the north (left) and south (right) lobes of Cen A. The peak at radio wavelength is described using synchrotron radiation, and the \(\gamma\)-ray spectrum is explained through \(p-p\) interactions.

(A color version of this figure is available in the online journal.)

| Lobs | Parameter Symbol | North Value | South Value |
|------|-----------------|-------------|-------------|
| Proportionality constant \((10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1})\) | \(A_{pp,\gamma}\) | 5.10 ± 0.96 | 8.07 ± 1.58 |
| Spectral index | \(\alpha\) | 2.519 ± 0.225 | 2.598 ± 0.254 |
| Chi-square/NDF | \(\chi^2/\text{NDF}\) | 2.748/4.0 | 0.555/3.0 |

Table 1

| Lobs | Parameter Symbol | North Value | South Value |
|------|-----------------|-------------|-------------|
| Proportionality constant \((10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1})\) | \(A_{\text{syn},\gamma}\) | 1.08 ± 0.30 | 4.51 ± 0.64 |
| Cut-off photon energy \((10^{-5} \text{ eV})\) | \(\epsilon_{\gamma,c}\) | 5.703 ± 0.557 | 4.01 ± 0.71 |
| Characteristic photon energy \((10^{-6} \text{ eV})\) | \(\epsilon_{\gamma,m}\) | 2.63 ± 0.03 | 3.48 ± 1.70 |
| Chi-square/NDF | \(\chi^2/\text{NDF}\) | 0.8616/2.0 | 1.290/4.0 |

Table 2
Figure 2. Plots of the best set of parameters (synchrotron cooling time ($t_{\text{syn}}$), electron density ($N_e$), and equipartition parameter ($\lambda_{e,B} = U_e/U_B$)) as a function of magnetic field ($B$) obtained with our synchrotron model for north (left) and south (right) lobes. (A color version of this figure is available in the online journal.)

where

$$A_{ic,\gamma} = \frac{\sqrt{8\pi} \sigma T}{9 q_e D^2} (1 + z)^{-1} \delta_B U_B^{-1/2} N_e r_d^3 U_{\gamma} E_{\gamma,k}, \quad (40)$$

and $U_{\gamma}$ is the photon energy density of CMB and EBL. Replacing the electron Lorentz factors and the typical photon energies of CBM and EBL (Dermer 2013; Equations (3) and (2)) in Equations (38)–(40) and from the best set of parameters, we plot these contributions as shown in Figure 3. In this
We can notice that a superposition of IC of CMB, EBL, and p–p interactions could satisfactorily describe the observed Fermi-LAT fluxes. Otherwise, p–γ interactions take place when accelerated protons collide with target photons. The single-pion production channels are $p + γ → n + π^+$ and $p + γ → p + π^0$, where the relevant pion decay chains are $π^0 → 2γ$, $π^+ → μ^+ + ν_μ$, $e^+ + ν_ν + \bar{ν}_ν$, and $π^- → μ^- + \bar{ν}_μ → e^- + \bar{ν}_ν + ν_ν$, respectively. Taking into account that $π^0$ carries 20% of the proton’s energy and that each produced photon shares the same energy, then the observed HE photon is given by

$$E_{γ, \text{HE}}^{\text{obs}} \simeq 0.5 \frac{\delta_D^2 (m_π^2 - m_p^2)}{(1 + z)^2} \left(E_{γ,\text{LE}}^{\text{obs}}\right)^{-1},$$  \hspace{1cm} (41)

where $E_{γ,\text{LE}}^{\text{obs}}$ corresponds to low-energy (LE) photons. Based on Equation (41), it is necessary that target photons should be in the energy range of $E_{γ,\text{LE}} \sim (30–400)$ MeV for a full description of γ-ray spectra. Although a more robust analysis should be done, such as a calculation of density of target photons, optical depth, rate of energy loss, etc., a simple calculation shows that this process needs seed photons with energies from tens to hundreds of MeV which is completely different from γ-ray spectra observed by LAT. Hence, there is no contribution of p–γ emission to the γ-ray spectra.

On the other hand, in addition to the analysis performed and shown here about the SED of the lobes, we are going to see whether there is any correlation of γ-ray spectra and UHECRs collected with PAO. Estimating the age of the lobes by means of synchrotron cooling time, $t_{\text{lobe}} \simeq t_{\text{syn}}$ (Hardcastle et al. 2009), and the acceleration (Equation (18)) and diffuse (Equation (18)) timescales with the magnetic field found, we obtain that the acceleration time, diffuse time, and the age of the lobes are 0.65 (0.37) Myr, 0.49 (0.89) Myr, and 55.1 (27) Myr for the north (south) lobe, respectively. Comparing the timescales, $t_{\text{acc}} \sim t_{\text{diff}} \ll t_{\text{lobe}}$, one can calculate that the maximum proton energies required are $E_p, \text{max} \approx 8.67(15.81) \times 10^{19}$ eV for the north (south) lobes, hence we demonstrate that protons could be accelerated up to energies as high as $10^{20}$ eV in the lobes. Following our analysis, we replace the fitting parameters $t_{\text{lobe}}, \alpha$, and $A_{p,γ}$ in Equations (27) and (25) to calculate the proton luminosity from $\sim$GeV to $10^{11}$ GeV and also estimate the number of UHE protons expected with PAO.

For this calculation, we take into account the thermal number density in the range $10^{-10} \text{ cm}^{-3} < n_p < 10^{-4} \text{ cm}^{-3}$. As shown in Figure 4, one can see that proton luminosity increases as thermal density decreases and it decreases as energy increases. In this plot, there are two interesting ranges, the GeV and EeV ranges. In the GeV range, which is connected directly with the Fermi fluxes, the proton luminosities in the north (south) lobe at some GeV energy are $3.7(7.7) \times 10^{43}$ erg s$^{-1}$ and $3.7(7.7) \times 10^{49}$ erg s$^{-1}$ for minimum ($n_p = 10^{-4} \text{ cm}^{-3}$) and maximum ($n_p = 10^{-10} \text{ cm}^{-3}$) thermal particle densities considered, and in the EeV range the luminosities are $3.11(2.31) \times 10^{19}$ erg s$^{-1}$ and $3.11(2.31) \times 10^{44}$ erg s$^{-1}$ for the same thermal particle densities. The values of luminosity at the GeV energy range are of the same order as those found by Hardcastle et al. (2009), Wykes et al. (2013), and Abdo et al. (2010a), and the EeV energy range is also in accordance with Hardcastle et al. (2009) and Dermer et al. (2009). In Figure 5, the number of events as a function of thermal density is plotted when a power law was considered. As shown, the expected number decreases as thermal particle density decreases, reaching a minimum value of 3.52 (north lobe) and 3.0 (south lobe) with a density equal to $10^{-4} \text{ cm}^{-3}$; see Table 3.

![Figure 3](https://example.com/figure3.png)

Figure 3. Fit of observed SED of the north (left) and south (right) lobes of Cen A. The component at higher energies is described through p–p interaction and IC (CBM and EBL). IC emission is plotted with our model and the parameters obtained in Tables 1 and 2.

(A color version of this figure is available in the online journal.)

| $n_p$ (cm$^{-3}$) | North Lobe Number of UHECRs | South Lobe Number of UHECRs |
|-----------------|-----------------------------|-----------------------------|
| $10^{-4}$       | 3.52                        | 3.00                        |
| $10^{-5}$       | 35.2                        | $3 \times 10^{-2}$         |
| $10^{-6}$       | 352                         | 300                         |
| $10^{-7}$       | $3.52 \times 10^{3}$        | $3.0 \times 10^{3}$        |
| $10^{-8}$       | $3.52 \times 10^{4}$        | $3.0 \times 10^{4}$        |
| $10^{-9}$       | $3.52 \times 10^{5}$        | $3.0 \times 10^{5}$        |
| $10^{-10}$      | $3.52 \times 10^{6}$        | $3.0 \times 10^{6}$        |

Table 3: Number of Expected Events (UHECRs) in PAO as a Function of Number Density of Thermal Particles from the North and South Lobe of Cen A.
Figure 4. Proton luminosity $L_p$ as a function of energy $E_p$ for the north (left) and south (right) lobes. These plots are generated as the thermal density range is $10^{-10}$ cm$^{-3} \leq n_p \leq 10^{-4}$ cm$^{-3}$.

(A color version of this figure is available in the online journal.)

Figure 5. Number of UHECRs expected as a function of number density of thermal particles ($n_p$) from the north (left) and south (right) lobes of Cen A.

(A color version of this figure is available in the online journal.)

Table 4

| Distributions of Pressures and Energies in the North and South Lobe of Cen A |
|---------------------------------|-----------------|-----------------|
|                                 | North Lobe      | South Lobe      |
| Non-thermal pressure (dyn cm$^{-2}$) | $P_{nth}$       | $5.4 \times 10^{-12}$ | $5.4 \times 10^{-12}$ |
| Thermal pressure (dyn cm$^{-2}$)  | $P_{th}$        | $0.9 \times 10^{-13}$ | $0.9 \times 10^{-13}$ |
| Proton density energy (erg cm$^{-3}$) | $U_p$           | $1.06 \times 10^{-12}$ | $1.07 \times 10^{-12}$ |
| Total energy (erg)               | $E_{tot}$       | $4.4 \times 10^{59}$   | $6.6 \times 10^{59}$   |

Note. These values have been obtained for volume, $1.3 \times 10^{71}$ cm$^{-3}$; number density of thermal particles, $n_p \sim 10^{-4}$ cm$^{-3}$; and temperature, $\sim 10^7$ K.

Considering a simple power law and the number density of thermal particles equal to $10^{-4}$ cm$^{-3}$, the result of the number of expected UHECRs is very similar to that reported by PAO. From Equations (20) and (21), and taking into account this number density, we estimate the pressures and energies in the lobes; see Table 4. As shown in Table 4, the bigger contribution of pressure exerted on the lobes comes from non-thermal particles and the contribution of protons to pressure and energy is significant although not dominant.

From this density and Equation (35), we calculate the number of neutrinos expected per year in IceCube for neutrino threshold energy equal to $E_{\nu,th} = 1$ TeV (see Table 5). In this table,
we can see that non-neutrinos are expected from the lobes. From Table 3, one can see that for any number density below $10^{-4}$ cm$^{-3}$, the expected UHECRs would be much higher than those reported by PAO, hence these densities should be excluded when a simple power law is considered, but not when we give careful consideration to a broken proton spectrum. In other words, taking into account a number density of less than $10^{-4}$ cm$^{-3}$, we could expect more or less events only when a broken proton spectrum is considered (Equations (26) and (27)). In Figure 6, contour plots of the broken spectrum parameters are plotted, with higher spectral index ($\beta$) and break energy ($E_{p,b}$) as a function of number density for which PAO would expect one and two events from each of the lobes. It can be seen in these graphs that $\beta$ is higher in the south lobe, as one event is expected and the number density is smaller. For instance, for the break proton energy ($E_{p,b} = 2.04 \times 10^{17}$ eV), we expect two events when $\beta = 3.28(3.29)$ and one event when $\beta = 3.47(3.48)$ for $n_p = 10^{-5}$ cm$^{-3}$ and two events when $\beta = 3.83(3.91)$ and one event when $\beta = 3.99(4.11)$ for $n_p = 10^{-6}$ cm$^{-3}$ from the north (south) lobe. From the analysis performed for

Figure 6. Contour plots of higher spectral index ($\beta$) and break energy ($E_{p,b}$) of the broken power law of accelerated protons (Equation (26)) for which PAO would expect one (above) and two (below) events from the north (left) and south (right) lobes, when the number density of thermal particles is $10^{-10}$ cm$^{-3} \leq n_p \leq 10^{-5}$ cm$^{-3}$. (A color version of this figure is available in the online journal.)

| Table 5 | Number of Neutrinos Expected on IceCube from the North and South Lobes of Cen A |
|---------|-------------------------------------------------|
| $E_{\nu, th}$ | North Lobe | South Lobe |
| 1 TeV | $N_{\nu}/(yr)^{-1}$ | $N_{\nu}/(yr)^{-1}$ |
| | $9.41 \times 10^{-2}$ | $7.47 \times 10^{-2}$ |

Note. This number is calculated by taking into account the number density of thermal particles and neutrino threshold energies equal to $n_p = 10^{-4}$ cm$^{-3}$ and $E_{\nu, th} = 1$ TeV, respectively.
the proton spectrum described by a BPL, one can see that it is more favorable when densities of thermal particles are higher.

Additionally, for this case we calculate the number of expected neutrinos in IceCube. From Equation (37), we plot the number of neutrinos as a function of time for a BPL as shown in Figures 7 and 8. Taking into account the parameters ($\beta$ and $E_{\nu,b}$) for one and two events from the north and south lobe, the events per year are reported in Tables 6 and 7. As shown in Figures 7 and 8, as $\beta$ and $E_{\nu,b}$ increase BPLs become closer to being overlapped. Assuming a threshold energy of $E_{\text{th},\nu} = 1\text{ TeV}$, it can be seen that less than 0.1 neutrinos are expected in IceCube.

5. SUMMARY AND CONCLUSIONS

In the framework of emission processes, we have done an exhaustive analysis to describe the photon spectrum of the lobes of Cen A. In our emission model, first we have used synchrotron radiation to fit WMAP data and then estimated the values of magnetic fields, electron number densities, as well as the age of the lobes; these values are calculated assuming an equipartition between the magnetic and electron energy density. As shown in Figure 2, these quantities are plotted as a function of magnetic field for a wide range. We estimate the values (see Section 4) based on the choices of equipartition parameters, 4.3 and 1.8
Figure 8. Number of neutrinos expected on IceCube when the neutrino threshold energy ($E_{\nu,th}$) is 1 TeV. These neutrinos are generated by $p$–$p$ interactions and normalized through $\gamma$-ray from north (left) and south (right) lobes. These figures show the number of neutrinos produced taking into account the parameters $\beta$ and $E_{p,b}$ of the broken power law of accelerated protons for which two UCHERs would arrive in PAO. We have used the values of parameters $\beta$ and $E_{p,b}$ given in Tables 6 and 7. (A color version of this figure is available in the online journal.)

...for the north and south lobes, respectively (Abdo et al. 2010a); therefore, the small difference regarding the estimation of the age of the north lobe given by Hardcastle et al. (2009) comes of our election, although the age of the south lobe as well as the values of electron number densities in the lobes are represented quite accurately (Wykes et al. 2013). Second, we have fitted Fermi-LAT data with $p$–$p$ interactions in order to obtain the proton luminosity and then the non-thermal and thermal pressure and total energy in the lobes. Although thermal particle densities in the range of $10^{-10} \text{ cm}^{-3} \leq n_p \leq 10^{-4} \text{ cm}^{-3}$ successfully describe the $\gamma$-ray spectrum, the density $n_p \sim 10^{-4} \text{ cm}^{-3}$ reproduces the value of proton luminosity $\sim 10^{43} \text{ erg s}^{-1}$ which is more realistic in connection with the jet power as well as non-thermal and thermal pressure and total energy which have been estimated through other methods (O’Sullivan et al. 2013; Stawarz et al. 2013, see Table 4). Again, one can see that the small differences come from the election of equipartition parameters and, consequently, the magnetic field.

...From the values of parameters found, we have explored some acceleration mechanisms of UHECRs and shown that protons can be accelerated inside the lobes up to energies as high as $\sim 10^{20} \text{ eV}$; then, we estimated the number of UHECRs expected in PAO, supposing that the proton spectrum extends up to this energy range. We found that few events can be expected on Earth...
Table 6
Number of Neutrinos above 1 TeV Expected Per Year from the North Lobe (See Figure 3, Left)

| β   | $E_{\nu, b}$ (eV) | $N_{ev}/T(\text{yr})^{-1}$ | β   | $E_{\nu, b}$ (eV) | $N_{ev}/T(\text{yr})^{-1}$ |
|-----|------------------|----------------------------|-----|------------------|----------------------------|
|     |                  | $n_p = 10^{-5}$ cm$^{-3}$   |     |                  | $n_p = 10^{-5}$ cm$^{-3}$   |
| BPL1| 2.87             | $0.5 \times 10^{13}$       | 2.81| $0.5 \times 10^{13}$                   | 9.11 $\times 10^{-2}$       |
|     |                  | $9.07 \times 10^{-2}$       |     |                  | $3.00 \times 10^{-2}$       |
| BPL2| 2.92             | $2.5 \times 10^{13}$       | 2.85| $2.5 \times 10^{13}$                   | 9.36 $\times 10^{-2}$       |
|     |                  | $9.35 \times 10^{-2}$       |     |                  | $3.07 \times 10^{-2}$       |
| BPL3| 2.95             | $0.5 \times 10^{14}$       | 2.88| $0.5 \times 10^{14}$                   | 9.38 $\times 10^{-2}$       |
|     |                  | $9.38 \times 10^{-2}$       |     |                  | $3.11 \times 10^{-2}$       |
|     |                  | $n_p = 10^{-6}$ cm$^{-3}$   |     |                  | $n_p = 10^{-7}$ cm$^{-3}$   |
| BPL1| 3.06             | $0.5 \times 10^{13}$       | 3.19| $0.5 \times 10^{13}$                   | 8.87 $\times 10^{-2}$       |
|     |                  | $8.94 \times 10^{-2}$       |     |                  | $3.29 \times 10^{-2}$       |
| BPL2| 3.14             | $2.5 \times 10^{13}$       | 3.29| $2.5 \times 10^{13}$                   | 9.32 $\times 10^{-2}$       |
|     |                  | $9.33 \times 10^{-2}$       |     |                  | $3.51 \times 10^{-2}$       |
| BPL3| 3.18             | $0.5 \times 10^{14}$       | 3.35| $0.5 \times 10^{14}$                   | 9.36 $\times 10^{-2}$       |
|     |                  | $9.37 \times 10^{-2}$       |     |                  | $3.59 \times 10^{-2}$       |
|     |                  | $n_p = 10^{-8}$ cm$^{-3}$   |     |                  | $n_p = 10^{-9}$ cm$^{-3}$   |
| BPL1| 3.44             | $0.5 \times 10^{13}$       | 3.58| $0.5 \times 10^{13}$                   | 8.71 $\times 10^{-2}$       |
|     |                  | $8.76 \times 10^{-2}$       |     |                  | $3.74 \times 10^{-2}$       |
| BPL2| 3.58             | $2.5 \times 10^{13}$       | 3.74| $2.5 \times 10^{13}$                   | 9.29 $\times 10^{-2}$       |
|     |                  | $9.30 \times 10^{-2}$       |     |                  | $3.83 \times 10^{-2}$       |
| BPL3| 3.66             | $0.5 \times 10^{14}$       | 3.83| $0.5 \times 10^{14}$                   | 9.35 $\times 10^{-2}$       |
|     |                  | $9.36 \times 10^{-2}$       |     |                  | $3.83 \times 10^{-2}$       |
|     |                  | $n_p = 10^{-10}$ cm$^{-3}$  |     |                  | $n_p = 10^{-11}$ cm$^{-3}$  |
| BPL1| 3.83             | $0.5 \times 10^{13}$       | 3.77| $0.5 \times 10^{13}$                   | 8.65 $\times 10^{-2}$       |
|     |                  | $8.63 \times 10^{-2}$       |     |                  | $3.96 \times 10^{-2}$       |
| BPL2| 4.03             | $2.5 \times 10^{13}$       | 3.96| $2.5 \times 10^{13}$                   | 9.28 $\times 10^{-2}$       |
|     |                  | $9.29 \times 10^{-2}$       |     |                  | $4.07 \times 10^{-2}$       |
| BPL3| 4.14             | $0.5 \times 10^{14}$       | 4.07| $0.5 \times 10^{14}$                   | 9.35 $\times 10^{-2}$       |

**Note.** Here, we show the parameters ($\beta$ and $E_{\nu, b}$) of the neutrino spectrum (Equation (36)) for three broken power laws (BPLs) when one and two UCHERs are expected in PAO.

... and only if the thermal particle density is again $\sim 10^{-4}$ cm$^{-3}$. However, we investigated the conditions for which few events would arrive taking into account densities $< 10^{-5}$ cm$^{-3}$. We consider a BPL for accelerating protons and made contour plots of the spectrum parameters (Figure 6) in which the higher spectral index ($\beta$) and the break energy ($E_{PB, b}$) for the expected number of UHERs would be one event for each of the lobes or two events for one lobe.

Correlating the $\gamma$-ray and neutrino fluxes, we have calculated the number of neutrinos expected in IceCube. We also considered a neutrino spectrum described by a simple and BPL, which is extended up to an energy range of IceCube. In both cases, the number of neutrinos per year would be less than $0.938 \times 10^{-1}$ and $0.745 \times 10^{-1}$ for the northern and southern lobes, respectively, which is consistent with the non-detection of HE neutrinos by IceCube in the direction of Cen A (IceCube Collaboration et al. 2013a, 2013b).

As shown in Figure 3, our model is consistent to describe the $\gamma$-ray spectrum with IC scattering of CMB and EBL first proposed and discussed by Abdo et al. (2010a) and Hardcastle et al. (2009). Additionally, we have briefly introduced $p-\gamma$ interactions and showed that they did not contribute to the $\gamma$-ray spectrum.

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**APPENDIX A**

**CHI-SQUARE MINIMIZATION**

First, from $p-p$ interaction model (Equation (13)), we fit the $\gamma$-ray spectrum using two parameters, the proportionality constant of $p-p$ spectrum $A_{pp, \gamma}$ (Equation (14)) and the spectral index $\alpha$, as follows:

$$\left(\frac{E_{\gamma}^2}{dN_{\gamma}}\right)_{\text{obs}}^{\text{obs}} = \left(\frac{E_{\gamma}^{\text{obs}}}{dE_{\gamma}}\right)_{\pi^0} = [0].$$

After fitting, we obtained the values. Second, from the synchrotron emission model (Equation (5)) and the value of $\alpha$ (Table 1), we fit the peak at radio wavelength using three parameters, the proportionality constant of synchrotron $A_{\text{syn}, \gamma}$ (Equation (6)), and the characteristic and cut-off photon energies $\epsilon_{\gamma, m}^{\text{obs}}$ and $\epsilon_{\gamma, c}^{\text{obs}}$ (Equation (3)), respectively, as follows:

$$e_{\gamma, m}^{\text{obs}} \leq [2],$$

$$\left(\frac{e_{\gamma}}{\epsilon_{\gamma, m}^{\text{obs}}}\right)^{4/3} \leq [2],$$

$$\left(\frac{e_{\gamma}}{\epsilon_{\gamma, c}^{\text{obs}}}\right)^{(\alpha-3)/2} \leq [1].$$

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Here, we show the parameters ($\beta$ and $E_{\nu,0}$) of the neutrino spectrum (Equation (36)) for three broken power laws (BPLs) when one and two UCHERs are expected in PAO.

### APPENDIX B

**NEUTRINOS BROKEN POWER LAW**

The number of HE neutrinos expected in IceCube from the north to south lobes is shown as follows.

### REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, Sci, 328, 725
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 719, 1433
Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, ApJL, 695, L40
Aharonian, F. A. 2002, MNRAS, 332, 215
Alvarez, H., Aparici, J., Ruiz, J., & Reich, P. 2000, A&A, 355, 863
Atoyan, A. M., & Dermer, C. D. 2003, ApJ, 586, 79
Arwert, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Baity, W. A., Rothschild, R. E., Lingenfelter, R. E., et al. 1981, ApJ, 244, 429
Becker, J. K. 2008, PhR, 458, 173
Birk, G. T., & Lesch, H. 2000, ApJL, 530, L77
Blumenthal, G. R., & Gould, R. J. 1970, RVMP, 42, 237
Bowyer, C. S., Lampton, M., Mack, J., & de Mendonca, F. 1970, ApJL, 161, L1
Brun, R., & Rademakers, F. 1997, NIMPA, 398, 81
Chaberge, M., Capetti, A., & Celotti, A. 2001, MNRAS, 324, L33
Cholis, I., & Hooper, D. 2013, ICAP, 6, 30
Combi, J. A., & Giannios, D. 1997, A&AS, 121, 11
Crusius, A., & Schlickeiser, R. 1986, A&A, 164, L16
Cuoco, A., & Hannestad, S. 2008, PhRvD, 78, 032007
Dermer, C. D. 2013, in Sources of GeV Photons and the Fermi Results, ed. F. Aharonian, L. Bergström, & C. Dermer (Berlin: Springer), 225
Dermer, C. D., & Menon, G. 2009, High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos (Princeton, NJ: Princeton Univ. Press)
Dermer, C. D., Razzaque, S., Finke, J. D., & Atoman, A. 2009, NJPh, 11, 065016
Engel, R. 2008, in International Cosmic Ray Conference, Vol. 4, Test of Hadronic Interaction Models with Data from the Pierre Auger Observatory, ed. R. Caballero, J. C. D’Olivo, G. Medina-Tanco et al. (Mexico City, Mexico: Universidad Nacional Autónoma de México), 385
Fraija, N. 2014, MNRAS, 437, 2187
Fraija, N., González, M. M., Perez, M., & Marinelli, A. 2012a, ApJ, 753, 40
Fraija, N., González, M. M., & Perez, M. 2012b, in Proc. of the Gamma Ray Bursts 2012 Conf. (Muñoz: PoS), 131
Gandhi, R., Quigg, C., Reno, M. H., & Sarcevic, I. 1998, PhRvD, 58, 093009
Georganopoulos, M., Sambruna, R. M., Kazanas, D., et al. 2008, ApJL, 686, L5
Giannios, D. 2010, MNRAS, 408, L46
Gorbunov, D., Tinyakov, P., Tkachev, I., & Troitsky, S. 2008, JETPL, 87, 461
Halzen, F. 2007, Ap&SS, 309, 407
Halzen, F. 2013, Riv. Nuovo Cimento, 036, 81
Halzen, F., & O’Murchadha, A. 2008, arXiv:0802.0887
Hardcastle, M. J., Birkinshaw, M., & Worrall, D. M. 2001, MNRAS, 326, 1499
Hardcastle, M. J., Cheung, C. C., Feain, I. J., & Stawarz, L. 2009, MNRAS, 393, 1041
Hardcastle, M. J., & Croston, J. H. 2011, MNRAS, 415, 133
Hardcastle, M. J., Kraft, R. P., Sikavikoff, G. R., et al. 2007, ApJL, 670, L81
Hardcastle, M. J., Kraft, R. P., & Worrall, D. M. 2006, MNRAS, 368, L15
Hardcastle, M. J., Worrall, D. M., Kraft, R. P., et al. 2003, ApJ, 593, 169
Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJ, 123, 79
Hauser, M. G., & Dwek, E. 2001, A&A, 39, 249
Hillas, A. M. 1984, A&A, 22, 425
Hinshaw, G., Weiland, J. L., Hill, R. S., et al. 2009, ApJS, 180, 225
Horiiuchi, S., Meier, D. L., Preston, R. A., & Tingay, S. J. 2006, PAST, 58, 211
IceCube Collaboration, Aartsen, M. G., Abbasi, R., et al. 2013a, Sci, 342, 1242856
IceCube Collaboration, Aartsen, M. G., Abbasi, R., et al. 2013b, arXiv:1304.5356
Israel, F. P. 1998, A&ARv, 8, 237
Junkes, N., Haynes, R. F., Hamett, J. I., & Jauncey, D. L. 1993, A&A, 269, 29
Kraft, R. P., Forman, W. R., Hardcastle, M. J., et al. 2009, ApJ, 698, 2036

### Table 7

| BPL1 | 2.88 | 0.5 × 10^{13} | 7.28 × 10^{-2} | 2.82 | 0.5 × 10^{14} | 7.32 × 10^{-2} |
| BPL2 | 2.93 | 2.5 × 10^{13} | 7.44 × 10^{-2} | 2.86 | 2.5 × 10^{14} | 7.45 × 10^{-2} |
| BPL3 | 2.95 | 0.5 × 10^{14} | 7.46 × 10^{-2} | 2.88 | 0.5 × 10^{14} | 7.46 × 10^{-2} |

### Note

Here, we show the parameters ($\beta$ and $E_{\nu,0}$) of the neutrino spectrum (Equation (36)) for three broken power laws (BPLs) when one and two UCHERs are expected in PAO.
