STUDY OF THE PEV NEUTRINO, $\gamma$-RAYS AND UHECRS AROUND THE LOBES OF CENTAURUS A

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ABSTRACT

Pierre Auger observatory reported the distribution of arrival directions of the highest energy cosmic rays. These events were collected in 10 years of operations with declinations between -90$^\circ$ and +45$^\circ$. The IceCube neutrino telescope reported the detection of 54 extraterrestrial neutrinos in the High-Energy Starting Events catalog. The highest-energy neutrino event (IC35) reported in this catalog had an energy of 2004$^{+236}_{-202}$ TeV and was located centered at RA=208.4$^\circ$ and DEC=−55.8$^\circ$ (J2000). Being Centaurus A the nearest radio-loud active galactic nucleus and one of the best potential candidates for accelerating cosmic rays up to $\sim 10^{20}$ eV, we show that UHECRs with $E > 58$ EeV around the direction of Centaurus A ($15^\circ$ radius) could be accelerated inside the giant lobes. Studying the composition of UHECRs through the photodisintegration processes due to Cosmic Microwave background photons and the average deflecting angles that nuclei undergo due to galactic and extragalactic magnetic fields, it is shown that the most promise candidates of UHECR composition are heavy nuclei, although small fractions of light nuclei such as nitrogen nuclei may be expected. These cosmic rays unavoidably interact with the external radiation fields and ambient gas whereas they propagate through the lobes and their paths to Earth. Using the buoyancy ages of the giant radio lobes instead of their spectral ages, and those UHECRs in the direction of the IC35 event, we found that the IC35 event cannot be generated inside the giant lobes. Additionally, considering the closest Galaxies around Centaurus A and the hadronic interactions in their paths to Earth, we found that IC35 event might be created in this environment.

Subject headings: Galaxies: active – Galaxies: individual (Centaurus A) – Physical data and processes: acceleration of particles — Physical data and processes: radiation mechanism: nonthermal – Neutrinos

1. INTRODUCTION

High-energy neutrino detections could give an indirect signal of ultra-high-energy cosmic ray (UHECR) acceleration. In particular, detection of PeV neutrinos created by interactions of UHECRs with ambient photons and matter at sources would probe places where CRs can be accelerated above $\sim 100$ PeV. However, sources of HE neutrinos as well as UHECRs remain unidentified. Large number of sources are extragalactic, such as active galactic nuclei (AGN; Rachen & Biermann 1993; Atoyev & Dermer 2001; Alvarez-Muniz & Mészáros 2004), gamma-ray bursts (GRB; Vietri 1995; Waxman 1995; Murase & Ioka 2013; Fraija 2013) and starburst galaxies (Loeb & Waxman 2006; Murase et al. 2013). The IceCube detector located at the South Pole published the High-Energy Starting Events (HESE)$^1$ catalog, a sample of 54 extraterrestrial neutrino events in the TeV - PeV energy range with three PeV events. The IC35 neutrino event centered at RA=208.4$^\circ$ and DEC=−55.8$^\circ$ (J2000) with a median angular error of 15.9$^\circ$ had the highest energy reported in this catalog which corresponds to 2004$^{+236}_{-202}$ TeV. Kadler et al. (2016) revised the second catalog of AGN reported by Fermi Large Area Telescope (LAT, 2LAC, Ackermann et al. 2011) and found 20 astrophysical sources associated to the median angular error of this event. The nearest AGN in the field of view of this event is Centaurus A (Cen A). Using the Fermi-LAT data collected from the core of Cen A, Saba et al. (2013) normalized the neutrino flux and found that the density required to observe high-energy neutrinos would have to be or the order of 10 - 100 cm$^{-3}$, thus discarding Cen A as a possible candidate to emit the IC35 neutrino event. The dominant blazar in the field of the IC35 neutrino event is PKS B1424-418 which was first discarded by Padovani & Resconi (2014) due to its low $\gamma$-ray emission. However, this source presented an outstanding flare beginning in summer 2012 and lasting for almost one year. Considering a photo-hadronic emission model, this event was linked to the giant outburst presented by this blazar which occurred in temporal coincidence (Kadler et al. 2016).

The Pierre Auger Observatory (PAO) located in Malargüe, Argentina, and with a duty cycle of nearly 100%, reported the distribution of arrival directions of the highest energy cosmic rays (Aab et al. 2015). Covering an area of $\sim 3000$ km$^2$ over 10 years of operations, from 2004 January 1$^{st}$ up to 2014 March 31, this observatory associated some UHECRs with energies larger than 58 EeV around the direction centered of Cen A.

Based on the analysis performed by PAO about the number of UHECRs larger around Cen A than the rest of the sky (Pierre Auger Collaboration & et al. 2007, 2008; Aab et al. 2015), this radio galaxy has been widely proposed as a potential source for emitting the UHECR events (e.g. Gorbunov et al. 2008; Moskalenko et al. 2009; Dermer et al. 2009; Fraija et al. 2012). At a distance of $d_*=3.8$ Mpc, Cen A (classified as Fanaroff & Riley Class I; Fanaroff & Riley 1974) has been one of the best studied extragalactic sources, characterized by having an off-axis jet of viewing angle which is estimated as $\sim 45^\circ$ (see, e.g. Horiiuchi et al. 2006, and reference

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therein) and two giant radio lobes of hundreds of kiloparsec. In the range of GeV - TeV energies, this source has been observed by Compton Gamma-Ray Observatory (CGRO) mission, Fermi Gamma-Ray Space Telescope and High Energy Stereoscopic System (H.E.S.S.) experiment. A number of different scenarios has been discussed to interpret the GeV-TeV energy range such as one-zone synchrotron self-Compton model (SSC; Abdo & et al. 2010b), external inverse Compton (Abdo & et al. 2010a), photodissociation of heavy nuclei (Kundu & Gupta 2013), proton-photon (pγ) (Fraija et al. 2012; Sahu et al. 2012; Petropoulou et al. 2014) and proton-proton (pp) interactions (Dermer et al. 2009; Fraija 2014). Requiring a satisfactory description of the γ-ray spectra with the hadronic models, some authors have extrapolated the power law of accelerated protons up to energies of \( \sim 10^{20} \) eV in order to explain the number of UHECRs observed by PAO (Fraija 2014; Petropoulou et al. 2014; Sahu et al. 2012).

In this paper, we investigate the possible association of UHECRs with the lobes of Cen A, the UHECR composition and also the conditions so that the PeV-neutrino event (IC35) reported in the H.E.S.E catalog by the IceCube Collaboration could be associated to UHECRs detected by PAO around the giant radio lobes of Cen A. In addition, we present a description of the faint γ-ray fluxes reported by Fermi Collaboration through the hadronic interactions inside the lobes. The paper is arranged as follows. In Section 2 we introduce relevant information about the giant lobes. In section 3 we present the deflection, composition, mechanism of acceleration and detection of UHECRs as well as the neutrino production through photo-hadronic and hadronic interactions. In Section 4 we show the analysis of UHECRs around the lobes. In Section 5 we present a description of the γ-ray fluxes reported by Fermi Collaboration. Section 6 shows the analysis of the PeV-neutrino production inside the lobes. Section 7 shows the analysis of neutrinos and UHECRs from the core emission. Section 8 presents the closest Galaxies around Cen A and the hadronic interactions in their paths to Earth, and Section 9 the conclusions. We hereafter present the equations in natural units and also the redshift \( z = 0.00183(2) \simeq 0 \).

2. GIANT LOBES OF CEN A

Cen A has two giant lobes which are subtended \( \sim 10^\circ \) (∼ 600 kpc in projection) on the sky (Israel 1998). They are connected to the energy supply jet and oriented in the north and south direction. Hardcastle et al. (2006) argued that the incoming jet goes through the northern inner lobe, enroled in the thermal interstellar gas of NGC5128, at \( \sim 3.5 \) kpc. Moreover, Hardcastle et al. (2007) proposed that the jet extends out to \( \sim 2.5 \) kpc in accordance to Chandra observations, exhibiting a similar scale to that observed in radio (Hardcastle et al. 2003; Tingay et al. 1998). Additionally, Kraft et al. (2009) considered the extended thermal X-ray emission and 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). Due to the lobes are inflated by jets into the surrounding medium, accelerated nuclei/protons are injected by the jet, and confined inside the lobes (Hardcastle et al. 2009). The non-thermal and the upper limit thermal pressure can be estimated by \( p_{\text{nth}} \simeq (U_e + U_B + U_A) \) and \( p_{\text{th}} = n_p T \), respectively, where \( U_A \sim 2L_A t_{\text{lobe}}/V \) is the accelerated-nuclei/proton energy density with luminosity \( L_A \), \( n_p \) is the particle density, \( T \) is the temperature and \( V \) is the volume of the giant lobes. Using the relationship between the magnetic field and the electron energy densities, \( U_e = \lambda_{e,B} U_B \) (Abdo & et al. 2010a; Fraija 2014), the non-thermal pressure and the total energy can be written as

\[
p_{\text{nth}} \simeq U_B (1 + \lambda_{e,B}) + 2L_A t_{\text{lobe}}/V, \tag{1}
\]

and

\[
E_{\text{tot}} \simeq U_B V (1 + \lambda_{e,B}) + 2L_A t_{\text{lobe}}, \tag{2}
\]

respectively.

Giant lobes have been detected in radio and γ-ray bands by the Parkes radio telescope (Junkes et al. 1993; Alvarez et al. 2000), the Wilkinson Microwave Anisotropy Probe (Hinshaw & et al. 2009; Page & et al. 2003; Hardcastle et al. 2009; Abdo & et al. 2010a) and Fermi-LAT (Atwood et al. 2009). This instrument measured fluxes of \( 0.77(+0.23/-0.19)_{\text{stat}}\,(\pm0.39)_{\text{syst}} \times 10^{-7}\,\text{ph}\,\text{cm}^{-2}\,\text{s}^{-1} \) and \( 1.09(+0.24/-0.21)_{\text{stat}}\,(\pm0.32)_{\text{syst}} \times 10^{-7}\,\text{ph}\,\text{cm}^{-2}\,\text{s}^{-1} \) for the northern and southern lobes, respectively (Abdo & et al. 2010a). They used a leptonic model to describe the electromagnetic emission from the lobes; Radio (WMAP) data through synchrotron radiation and Fermi-LAT data by inverse Compton-scattered (IC) radiation from the cosmic microwave background (CMB) and extragalactic background light (EBL). Fraija (2014) evoked a lepto-hadronic model to describe the spectral energy distribution (SED) of the giant lobes; synchrotron radiation to explain the radio wavelength emissions and pp interactions to fit the γ-ray fluxes.

Based on dynamical and buoyancy arguments, Wykes et al. (2013) inferred that the sound-crossing and buoyancy ages of the giant lobes are \( \sim 440 - 645 \) Myr and \( \sim 560 \) Myr, respectively. On the other hand, some authors considered the synchrotron process to describe the radio wavelengths observed in the lobes and found that the spectral ages are 21 - 55 Myr and 24 - 27 Myr for the northern and southern giant lobes, respectively (Hardcastle et al. 2009; Fraija 2014). Table 1 shows the parameters derived from observations of the giant lobes.

### Table 1

| Giant lobes | Northern | Southern |
|------------|----------|----------|
| Magnetic field (\( \mu \text{G} \)) | B | 0.9 - 3.4 | 0.9 - 6.2 | (1,2) |
| Equipartition parameter | \( \lambda_{e,B} \) | 4.3 | 1.8 | (1) |
| Density particles (\( \text{cm}^{-3} \)) | \( n_p \) | \( 10^{-11} - 10^{-4} \) | \( 10^{-11} - 10^{-4} \) | (3,4,5) |
| Size of the Lobes (kpc) | \( R \) | 100 - 230 | 100 - 220 | (1,3) |
| Age of the lobes | | | |
| Spectral arguments (Myr) | \( t_{\text{lobe}} \) | 21 - 55 | 24 - 27 | (2,3) |
| Buoyancy arguments (Myr) | \( t_{\text{lobe}} \) | \( \sim 600 \) | \( \sim 600 \) | (5) |

References. (1) Abdo & et al. (2010a) (2) Fraija (2014) (3) Hardcastle et al. (2009) (4) Slawizki et al. (2013) (5) Wykes et al. (2013)

3. COSMIC RAY AND NEUTRINO EVENTS

3.1. UHE cosmic rays

3.1.1. Deflection and Composition

UHECRs traveling from the lobes of Cen A to Earth are randomly deviated between the original and the observed arrival direction due to the strengths and geometries of magnetic fields: extragalactic and galactic (Das et al. 2008; Ryu et al. 2010), Galactic winds (Heesen et al. 2016; Li et al. 2016; Wiegert et al. 2016), magnetic winds (Parker 1958; Everett & Zweibel 2011) and magnetic turbulence (Federrath 2013;
for photodisintegration processes with CMB photons is obtained energy. The time scale of the effective energy loss with
\[ \epsilon \]
(Dermer 2008)
\[ \delta \]
produced by the weak (might have deflexions as large as (or even larger than) those
of dozens of kpc) by the stronger magnetic field (\( L_B \)). The photodisintegration cross section of a
these interact with CMB and EBL (Stecker & Sala-
Nuclei experiment photodisintegration processes when
(Arisaka et al. 2007).

Due to Cen A is located at 19.4° from the galactic plane and
43.1° from the central galaxy, UHECRs coming from this
radio galaxy could undergo large deflexions in their paths (\( \sim 1 - 4\mu G \))
with the weaker \(( \sim nG \)) extragalactic magnetic field (\( G \)).
The strength of CRs might produce large deflexions as large as (or even larger than) those
produced by the weak (\( \sim nG \)) extragalactic magnetic field
in larger trajectories. It is worth noting that the strength of
galactic magnetic field on the plane is higher than magnetic
field in the halo, and the paths from this radio galaxy have
to cross twice the size of our galaxy (Fargion 2008).

The composition of UHECRs is not clear and it is under
debate. Studies reported by observatories as AGASA (Shinozaki et al. 2006), Yakutsk (Knurenko et al. 2008) and others
(Sokolsky & Thomson 2007; Abbasi et al. 2005) suggested
that at the highest energies the UHECR composition was dominated by protons. However, others experiments such as PAO have suggested that the UHECR composition at the highest energies was dominated by heavier or mixed composition (Unger et al. 2007) and recently by light nuclei
(Aab et al. 2014). This Collaboration analyzed data from
December 2004 to December 2012 in order to examine the
implications of the depth distributions in the atmosphere for
composition of the primary cosmic rays. They evaluated
several hadronic interaction models and analyzed the quality
of fit in the whole energy range. They found that whereas data were not adjusted by a mix of proton (p) or iron (Fe) nuclei,
light nuclei such as helium (He) and nitrogen (N) described
successfully data at the highest energies. In fact, using He nuclei data were fitted in almost the entire energy range by
all hadronic models. It is worth noting that the interpretation
of the results depends on the hadronic interaction model used
to extrapolate the information of the cross section up to the
highest energies. Therefore, important details about chemical
composition in the extrapolated data could be misunderstood
(Arisaka et al. 2007).

Nuclei experiment photodisintegration processes when
these interact with CMB and EBL (Stecker & Salamon 1999).
The photodisintegration cross section of a nucleus \( A \) is
\[ \sigma_A(\epsilon_r) \sim 35.5\text{mb}\delta(\epsilon_r - 83.5A^{-0.21}) \]
with \( \epsilon_r = \gamma(1 - \mu) \) the invariant dimensionless photon energy. The time scale of the effective energy loss for photodisintegration process with CMB photons is
\[ \epsilon \]

where \( w(\epsilon) = \frac{0.83A^{0.79}}{1+z}E_{20} \) and where \( k \) is 1.2, 3.6 and 4.349 for
He, N and Fe, respectively (Dermer & Menon 2009). The mean free path for photodisintegration in the \( \delta \)-function is

Although there is not photodisintegration process for protons, these lose their energies when interacting with CMB photons.
The mean free path for photopion energy losses is (Dermer 2007; Dermer & Menon 2009)
\[ \lambda_\nu(E) \sim \frac{13.5 e^{\frac{4E}{20}}}{E_{20}} \text{Mpc} . \]

In equations (4) and (3), the notation \( E_{20} = \frac{E}{10^{20}\text{eV}} \) has been used.

3.1.2. Mechanisms of Acceleration

The maximum energies that CRs can reach within the lobes are limited by their sizes (R) and the strength of magnetic fields (B). The maximum energy (so-called Hillas condition, Hillas 1984) can be written as

\[ E_{Z,max} = \frac{ZeB R \Gamma}{\delta} \]

where \( \Gamma = 1/\sqrt{1 - \beta^2} \) is the Lorentz factor. The acceleration timescale \( t_{acc} \approx \eta R_g \) with \( R_g = \frac{E_{max}}{ZeB} \) is given by

\[ t_{acc} \approx \frac{\eta E_{Z,max}}{ZeB} \]

where \( \eta \gtrsim 1 \) is the gyromagnetic factor. CRs can escape from the lobes only by diffusion \( t_{esc} \approx \frac{R^2}{2D(\epsilon)} \), where
\( D(\epsilon) = \frac{1}{2} \eta R_g \) is the diffusion coefficient. Therefore, the escape timescale can be written as

\[ t_{esc} \approx \frac{3eZ R^2 B}{2\eta E_{Z,max}} \]

During the flaring events, CRs could be also accelerated up to
UHEs. From the equipartition magnetic field parameter \( (\epsilon_B) \) and the apparent isotropic luminosity \( (L_A) \) during the flaring intervals, the maximum particle energy of accelerated CRs can be given by (Dermer et al. 2009)

\[ E_{Z,max} \approx \frac{eZ \sqrt{\epsilon_B L_A}}{\phi \beta^{-4/3} \Gamma} \]

where \( \phi \approx 1 \) is the acceleration efficiency.

Other mechanisms of acceleration proposed to accelerate CRs in the giant lobes have been the magnetic reconnection and the stochastically acceleration by temperature gradient. In the magnetic reconnection framework, the free energy stored in the helical configuration can be converted to particle kinetic energy, resulting in continuously charged particle acceleration (Birk & Lesch 2000; Giannios 2010; Wykes et al. 2013). Stochastic acceleration of CRs by high temperatures has been proposed by Wykes et al. (2013). In this mechanism, CRs could be stochastically accelerated, being responsible for the self-consistency between the entrainment calculations and the missing pressure in the lobes. O’Sullivan et al. (2009) investigated the acceleration of particles via the second-order Fermi process in the lobes. They concluded that considering this process, the maximum energy reached by CRs was in the energy range relevant for the Pierre Auger events.

Irrespective of the acceleration mechanisms, Waxman (1995) showed that the magnetic luminosity needed to accelerate nuclei/protons up to the energy range observed by PAO in the laboratory frame was given by the inequality \( L_{Z,B} \geq 10^{45} Z^{-2} (\frac{E}{10^{20}\text{eV}}) \text{erg/s} \).
3.1.3. UHECR Luminosity

Cen A has been proposed as a potential source for studying the UHECR events (Gorbunov et al. 2008; Moskalenko et al. 2009; Dermer et al. 2009; Fraija et al. 2012). Recently, Aab et al. (2015) reported the distribution of arrival directions of UHECRs collected with PAO in 10 years of operations. To determine the number of UHECRs, we use the PAO exposure, which for a point source is given by

\[ L_A = 4\pi d_A^2 \frac{\epsilon_0}{\omega(\delta_0)} \frac{\alpha_A - 1}{\alpha_A - 2} E_{\nu,\text{th}}^{-1+\alpha_A} N_{\nu,\text{obs}} E_A^{-\alpha_A} \]

where this equation is normalized with the number of UHECRs \( N_{\nu,\text{obs}} \) to be found in the direction of interest.

3.2. Neutrinos

At the giant lobes, CRs unavoidably interact with external radiation fields and ambient gas whereas they propagate through them. In this case, HE neutrinos are produced inside and outside the lobes.

3.2.1. Photo-hadronic interactions

Accelerated nuclei/protons interact with EBL and CBM photons by photo-hadronic interactions. Following Murase et al. (2014), the neutrino spectrum can be obtained by means of the nuclear/proton spectrum given by

\[ E_{\nu} L_{\nu} \simeq \frac{3}{8} f_{A\gamma} E_A L_A \]

where \( f_{A\gamma} \simeq \min\{\sigma_{A\gamma}^{\nu}, n_\gamma, R, 1\} \) is the photomeson production efficiency, with \( n_\gamma \) the photon density of CMB and EBL, and \( \sigma_{A\gamma}^{\nu} \) is the photomeson production cross section, with \( \sigma_{A\gamma}^{\nu} \simeq 5 \times 10^{-28} \text{ cm}^2 \text{ A}^{-1} \text{ GeV}^{-1} \) and \( \epsilon_{\gamma,\nu} \simeq 0.3 \text{ GeV} \) and \( \epsilon_{\nu,\nu} \simeq 0.2 \text{ per nucleon} \). The characteristic neutrino energy can be roughly estimated as

\[ \epsilon_{\nu,\nu} \simeq 0.25 \epsilon_{\gamma,\nu} \delta_D (m_D^2 - m_B^2) \epsilon_{\gamma,\nu}^{-1} \]

where \( m_D \) and \( m_B \) are the resonance and proton masses, \( \epsilon_{\gamma,\nu} \) is the peak photon energy of EBL and CBM, and \( \delta_D \) is the Doppler factor.

3.2.2. Hadronic interactions

Accelerated nuclei/protons interact with the ambient internal density protons. The neutrino spectrum can be obtained by means of the nuclear/proton spectrum given by

\[ E_{\nu} L_{\nu} \simeq f_{A} E_A L_A \]

where \( f_A \simeq \min\{\sigma_A n_B t_{\text{lobes}}, 1\} \) is the production efficiency of this process with \( \sigma_A \simeq 8 \times 10^{-28} \text{ cm}^2 \text{ A}^{-1} \text{ at } \sim 100 \text{ PeV} \), \( n_B \) is the proton density and \( t_{\text{lobes}} \) is the age of the giant lobes.

3.2.3. Expected neutrino events

The number expected of shower-like \( \nu \) events in IceCube telescope is

\[ N_{\nu} \approx T \int_{E_{\nu,\text{min}}}^{E_{\nu,\text{max}}} A_{\text{eff}} \left( \frac{dN_\nu}{dE_\nu} \right) dE_\nu, \]

where \( T \approx 4 \text{ years} \) is the days lifetime for HESE catalog, \( A_{\text{eff}} \) is the neutrino effective area for the shower-like events in the declination of Cen A (see Figure 2) and \( dN_\nu/dE_\nu \) is the neutrino spectrum which can be written as

\[ \frac{dN_\nu}{dE_\nu} = A_\nu \left( \frac{E_\nu}{100 \text{ TeV}} \right)^{-\alpha_\nu}, \]

with \( \alpha_\nu \) the neutrino power index, \( E_{\nu,\text{max}} \) and \( E_{\nu,\text{min}} \) for the maximum and minimum neutrino energy, respectively. The normalization constant \( A_\nu \) is estimated to be

\[ A_\nu \simeq \frac{L_\nu}{4\pi d_A^2} \int_{E_{\nu,\text{min}}}^{E_{\nu,\text{max}}} \frac{E_\nu}{100 \text{ TeV}}^{-\alpha_\nu} dE_\nu. \]

4. COSMIC RAYS ANALYSIS IN THE LOBES

4.1. Timescales, Composition and Deflexion

In subsection 3.1.2, some mechanisms that could accelerate CRs up to UHEs have been presented. As follows, we show that nuclei/protons can be accelerated up to ultra-relativistic energies inside the giant lobes and also are able to escape from them. Using the values reported of the giant lobes (see Table 1), then the maximum nuclei energy reached by stochastic processes inside the giant lobes is

\[ E_{Z,\text{max}} = 0.92 \times 10^{20} \text{ eV } \frac{B}{1 \mu \text{G}} \left( \frac{R}{100 \text{ kpc}} \right) \left( \frac{\Gamma}{1} \right), \]

and/or during flaring events the maximum nuclei/proton energy is

\[ E_{Z,\text{max}} \approx 0.9 \times 10^{20} \text{ eV } Z \beta^{-3/2} \epsilon_B^{1/2} \left( \frac{L}{10^{45} \text{ erg}/\text{s}} \right)^{1/2} \left( \frac{\Gamma}{1} \right)^{-1}. \]

It is important to note that using the value of magnetic field of \( \sim 10^{-5} \mu \text{G} \) inferred from the synchrotron emission at the radio bands in the Northern middle lobe (Romero et al. 1996), Lemoine & Waxman (2009) showed that the Larmor radius was \( R_g \approx 11 \text{ kpc} \), concluding that the Hillas criterion was not satisfied. However, recent observations of radio wavelengths and \( \gamma \)-rays emanating from the giant radio lobes of Cen A provided values of the magnetic fields and particle energy content in these lobes. Abdou et al. (2010a) reported values of magnetic fields of 0.89 \( \mu \text{G} \) and 0.85 \( \mu \text{G} \) for the northern and southern lobes respectively. Considering the new values of magnetic fields, the Larmor radius becomes \( \sim 100 \text{ kpc} \), thus satisfying the Hillas criterion.

Equations (16) and (17) indicate that the maximum energies for \( Z \geq 2 \) are in agreement with the highest energy cosmic rays detected by PAO around the direction of Cen A\(^2\). These equations show that protons can hardly be accelerated up to energies of 10\(^{20} \) eV or more. The acceleration timescales in

\(^2\) The maximum nuclei/proton energy derived through the Hillas criterion does not change if the equation \( E_{Z,\text{max}} = Z e B R \beta/\Gamma \) is used as suggested by Lemoine & Waxman (2009).
the giant lobes for ultra-relativistic nuclei are

\[ t_{Z,\text{acc}} \simeq 0.4 \text{ Myr} \ Z^{-1} \eta \left( \frac{E_{Z,\text{max}}}{10^{20} \text{eV}} \right) \left( \frac{B_1}{\mu \text{G}} \right)^{-1}, \]

which is much smaller than the ages reported for the giant lobes (see Table 1). The characteristic timescales of diffusive escape for nuclei are

\[ t_{Z,\text{esc}} \simeq 0.4 \text{ Myr} \ Z^{-1} \eta \left( \frac{R}{100 \text{kpc}} \right)^2 \left( \frac{E_{Z,\text{max}}}{10^{20} \text{eV}} \right) \left( \frac{B_1}{\mu \text{G}} \right)^{-1}. \]

The comparison between the timescales \( t_{Z,\text{acc}} \approx t_{Z,\text{esc}} \ll t_{\text{lobe}} \) indicates that nuclei can be accelerated up to \( \sim 0.9 \times 10^{20} \text{eV} Z \) before they escape from the giant lobes. The value of the gyromagnetic factor for \( t_{Z,\text{acc}} \approx t_{Z,\text{esc}} \) is \( \eta \simeq Z \left( \frac{R}{100 \text{kpc}} \right) \left( \frac{E_{Z,\text{max}}}{10^{20} \text{eV}} \right)^{-1} \), which lies in the Bohm diffusion limit and is independent of \( Z \). This limit gives account that nuclei are efficiently accelerated in the lobes, thus being able to explain the UHECR flux in the direction around Cen A.

In order to determine the number of UHECRs around Cen A, an estimation of the maximum deflection angle is given through the galactic and extragalactic magnetic fields. In the galactic disk, the magnetic field immersed in it is arranged in a spiral and its lines are frozen (from left to right) within the plane. Hence, UHECRs can move randomly to and fro in a vertical direction, filling the supergalactic plane (Fargion 2008). The magnetic field in our Galaxy has been more studied that the extragalactic magnetic field. In our Galaxy, the strength of the field can be estimated, in principle, considering the pulsar rotation and the dispersion measurements associated with the distribution of free electrons (Cordes & Lazio 2003, 2002). The orientation of the field which indicates that it increases towards the inner Galaxy has been inferred by simultaneous studies of synchrotron radiation in the radio wavelengths, cosmic rays and \( \gamma \)-ray data. Using the values of galactic magnetic field in the halo and on the plane with a coherence length \( \sim 1 \text{kpc} \), the average deflecting angles in our Galaxy due to galactic magnetic field in the halo is (Fargion 2008)

\[ \theta_{Z,G} \gtrsim 1.38^\circ Z \left( \frac{E_{A,\text{th}}}{58 \text{EeV}} \right)^{-1} \left( \frac{B_G}{1 \mu \text{G}} \right) \sqrt{\frac{L_G}{10 \text{kpc}}} \left( \frac{l_{c,G}}{\text{kpc}} \right), \]

and on the plane is

\[ \theta_{Z,G} \gtrsim 3.9^\circ Z \left( \frac{E_{A,\text{th}}}{58 \text{EeV}} \right)^{-1} \left( \frac{B_G}{4 \mu \text{G}} \right) \sqrt{\frac{L_G}{20 \text{kpc}}} \left( \frac{l_{c,G}}{\text{kpc}} \right). \]

Considering the larger values of the average deflecting angles in our Galaxy, it is worth emphasizing that galactic magnetic field may create a strong shadowing effect on the true location of sources. For an event traveling a distance of 3.8 Mpc, the mean-square deviation due to the extragalactic magnetic field \( (B_{EG} \sim 1 \text{nG}) \) with a coherence length of \( l_{c,EG} \sim 1 \text{Mpc} \) is (Fraija et al. 2017)

\[ \theta_{B,G} \gtrsim 2.5^\circ Z \left( \frac{58 \text{EeV}}{E_{p,\text{th}}} \right)^{-1} \left( \frac{B_{EG}}{\text{nG}} \right) \sqrt{\frac{L_{EG}}{100 \text{Mpc}}} \left( \frac{l_{c,EG}}{1 \text{Mpc}} \right). \]

The average deflecting angles show that when the UHECRs go through a magnetic field, heavy nuclei are deflected at larger angles than light nuclei. As expected, the average deflecting angles due to galactic magnetic field on the plane is larger than that in the halo, and even larger than the extragalactic magnetic field. Considering only the galactic magnetic field on the plane, the average deflecting angles are \( \theta_{Z,G} \gtrsim 3.9^\circ, 7.8^\circ, 23.3^\circ \) and 101.4° for proton, helium, nitrogen and iron nuclei, respectively. Therefore, UHE iron nuclei going through the galactic plane can hardly arrive on Earth in a radius less than \( \lesssim 15^\circ \), and UHE nitrogen nuclei only a small fraction. Ryu et al. (2010) found that the deflection angle between the arrival direction and the original position for UHE protons and the lightest nuclei can be as large as \( < \theta_T \sim 15^\circ \).

On the other hand, using the values of magnetic fields reported in Table 1, the magnetic luminosity becomes

\[ L_B = \pi R^2 \Gamma \frac{B^2}{8 \pi} \simeq 3.6 \times 10^{44} \text{ erg s}^{-1} \left( \frac{R}{100 \text{kpc}} \right)^2 \left( \frac{B}{\mu \text{G}} \right)^2 \left( \frac{1}{10^2} \right)^2. \]

Considering the condition for accelerating UHE protons and nuclei, the magnetic luminosities are \( L_B \gtrsim 10^{46} \text{ erg s}^{-1}, 2.5 \times 10^{44} \text{ erg s}^{-1}, 2.1 \times 10^{43} \text{ erg s}^{-1} \) and \( 1.4 \times 10^{40} \text{ erg s}^{-1} \) for proton, helium, nitrogen and iron nuclei, respectively. Comparing the magnetic luminosity in Cen A, protons from this radio galaxy would be again excluded as potential candidates of UHECRs.

Figure 3 shows the energy-loss mean free path for photodisintegration processes with CMB photons as a function of energy for helium, nitrogen and iron nuclei. In addition, the mean free path of protons for photopion energy losses due to CMB photons is displayed. Based on the interactions with CMB photons, the most significant contribution of helium, nitrogen and iron nuclei/protons to UHECR composition has as origin sources located to distances less than 5 Mpc, 100 Mpc and 150 - 400 Mpc, respectively. It is important to highlight that any fraction of UHE helium nuclei detected on Earth must come from close sources (\( \lesssim 5 \text{Mpc} \)), and fractions of UHE iron nuclei and protons from sources longer than \( \gtrsim 150 \text{ Mpc} \). Considering UHECR events to distances less than \( \lesssim 75 - 100 \text{ Mpc} \), a degree of anisotropy in a particular direction is expected. Taking into consideration our analysis around the maximum nuclei/proton energy reached in the giant lobes with their timescales, the average deflecting angles, the magnetic-field luminosity condition and the energy-loss mean free path for photodisintegration processes, it can be inferred that inside a radius of \( \sim 15^\circ \) centered around Cen A, UHE helium nuclei are the most promising candidates, UHE iron nuclei and protons are excluded and UHE nitrogen nuclei could contribute with a small fraction. Therefore, our model is consistent with the results recently reported by Aab et al. (2014) concerning to the UHECR composition at the highest energies.

### 4.2. CR Luminosities at lower energies

Figure 4 shows a sky-map with 231 UHECRs collected by PAO and the giant lobes of Cen A. The contour of the large-scale structure of the giant lobes at 1.4 GHz was considered (Hardcastle et al. 2009). Due to the average deflection angles produced by galactic and extragalactic magnetic fields between Cen A and Earth, a circle of \( 15^\circ \) around Cen A was considered. The numbers of UHECRs inside the circular region centered at Cen A are 14.

Column 4 in Table 2 shows the UHECR luminosity at 1 EeV for power indexes \( \alpha_A = 2.2, 2.4 \) and 2.6, and \( N_{\text{cr}}^{\text{obs}} = 14 \).
In addition, columns 2 and 3 show the CR luminosities at 1 TeV and 100 PeV, respectively, which were calculated extrapolating the UHECR luminosity at these lower energies. The number of UHECR events and the UHECR luminosity would have been increased by a factor of 1.5 - 2 if a deflexion angle around 18° would have been considered. It is worth noting that the UHECR luminosity $\sim 10^{40} - 10^{41}$ erg/s at 1 EeV corresponds to one of the principal sources of UHECR emissivity inside $\sim 10$ Mpc (Waxman & Bahcall 1998).

The monitoring time depends on the declination. Given the latitude of the Pierre Auger observatory ($L = S 69^\circ 18^\prime 41^\prime\prime$) sky regions at declination $\delta \lesssim -20^\circ$ are circumpolar, and regions between declinations approximately $\pm 20^\circ$ are visible only a fraction of a day. If $\alpha$ is the elevation of a cosmic ray above the horizon, then

$$\sin \alpha = \sin L \sin \delta + \cos L \cos \delta \cos h,$$

where $\cos h$ is the hour angle. Making the elevation $\alpha = 0^\circ$, we obtain

$$\cos h = \tan L \tan \delta,$$

which solutions correspond to the rise and setting associated to a given sky declination. For each detected cosmic ray we define a weight $\omega$ depending on the declination to compensate for partial monitoring. Therefore, every cosmic ray count will be multiplied for its corresponding weight:

$$\text{If } \delta \leq -90^\circ - L, \text{ then, } \omega = 1.$$  
$$\text{Otherwise, } \omega = \frac{\pi}{\arccos(-\tan L) \tan \delta}.$$

We exclude cosmic rays above $\delta > 0$ to avoid poor monitored regions which might bias the results. With this cosmic ray selection, all the weights are $w < 2$. Let $n_\Omega$ and $n_\Theta$ be the number of weighted counts in the target and background regions with solid angles $\Omega$ and $\Theta$ respectively, and let the total number of weighted cosmic rays in these two regions be $N = n_\Omega + n_\Theta$.

Our test consists of comparing the cosmic ray counts $n_\Omega$ detected in the $\Omega$ solid angle, with the expectation for a uniform distribution of cosmic rays given by $N$ counts in a solid angle $\Omega + \Theta$. The null hypothesis of the test is that the probability that a cosmic ray hits the region of solid angle $\Omega$ depends only on the involved solid angles, that is

$$p(\Omega) = \frac{\Omega}{\Omega + \Theta}.$$  

The alternative hypothesis is that the actual probability is larger than $p(\Omega)$. We chose a significance level of $\alpha = 0.001$ (approximately $3\sigma$), that is the probability of rejecting the null hypothesis when it should be accepted (i.e., the probability of a Type I error).

Under the null hypothesis, the $n_\Omega$ counts are binomial distributed with number of trials $N$ and probability $p(\Omega)$: $n_\Omega \sim \text{Binomial}(N, p(\Omega))$. Thus the procedure is to perform a test for $n_\Omega$ counts on this binomial distribution. In R-code the test can be calculated using the binom.test (stats) function binom.test(round(n_\Omega), round(n_\Omega + n_\Theta), p(\Omega), alternative = "g"), where the function round is necessary to ensure integer values for the weighted cosmic ray counts. Alternatively, the R-function poisson.test(stats) yields the same result poisson.test(round(n_\Omega), m_\Omega), alternative="g"). We perform this procedure to compare different regions centered on Cen A to test for overabundances of cosmic ray detections as a function of the source separation, as shown in Figure 1.

| Proton Luminosity at Different Energies. |
|---|
| $\alpha$ |
| 1 TeV | 100 PeV | 1 EeV |
| 2.2 | $1.1 \times 10^{41}$ | $1.1 \times 10^{40}$ | $7.2 \times 10^{39}$ |
| 2.4 | $2.3 \times 10^{42}$ | $2.4 \times 10^{41}$ | $9.4 \times 10^{39}$ |
| 2.6 | $6.4 \times 10^{43}$ | $6.4 \times 10^{42}$ | $1.6 \times 10^{40}$ |

4.3. Statistics Analysis

The problem of comparing the results of two Poisson events samples has been addressed by several authors. To mention a few, Przyborowski & Wilenski (1940) introduced the conditional test using the binomial distribution. Cox (1953) presented a procedure based on the $F$-distribution; more recently Krishnamoorthy & Thomson (2004) introduced a test based on the standardized difference between the two samples, and Chui (2010) used bootstrap. The conditional test is the most widely used to compare Poisson distributions, and it is implemented in the R-language as the poisson.test (stats) function. However, the conditional test as presented in Przyborowski & Wilenski (1940) is rather cumbersome, thus we have developed a more intuitive implementation. Note that our implementation is rigorously equivalent to the Przyborowski & Wilenski (1940) procedure.

First, we must define the two samples to be compared. The first one comprises the cosmic rays detected in a solid angle of radius $\theta$ around the AGN, which corresponds to a solid angle:

$$\Omega(\theta) = 2\pi(1 - \cos \theta) \text{ sr}.$$

The second sample will be used as a control to estimate the cosmic ray background, and it includes the cosmic ray events distributed across the southern sky hemisphere except the region of $40^\circ$ around the AGN. This corresponds to a solid angle:

$$\Theta = 2\pi - \Omega(40^\circ) = 4.813199 \text{ sr} \equiv 15800.8 \text{ deg}^2.$$

The alternative hypothesis is that the actual probability is larger than $p(\Omega)$. We chose a significance level of $\alpha = 0.001$ (approximately $3\sigma$), that is the probability of rejecting the null hypothesis when it should be accepted (i.e., the probability of a Type I error).

Under the null hypothesis, the $n_\Omega$ counts are binomial distributed with number of trials $N$ and probability $p(\Omega)$: $n_\Omega \sim \text{Binomial}(N, p(\Omega))$. Thus the procedure is to perform a test for $n_\Omega$ counts on this binomial distribution. In R-code the test can be calculated using the binom.test (stats) function binom.test(round(n_\Omega), round(n_\Omega + n_\Theta), p(\Omega), alternative = "g"), where the function round is necessary to ensure integer values for the weighted cosmic ray counts. Alternatively, the R-function poisson.test(stats) yields the same result poisson.test(round(c(n_\Omega, n_\Theta)), c(\Omega, \Theta), alternative="g"). We perform this procedure to compare different regions centered on Cen A to test for overabundances of cosmic ray detections as a function of the source separation, as shown in Figure 1.

5. HIGH-ENERGY $\gamma$-RAY FLUX ANALYSIS IN THE LOBES

The Fermi Collaboration reported $\gamma$-ray excesses with energies larger than $\geq 100$ MeV for both lobes of Cen A (Abdo & et al. 2010a). The faint $\gamma$-ray fluxes at 5 GeV were $F_{\gamma\nu} \approx 4.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $\approx 1.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$
Neutrinos from Centaurus A

7

which correspond to photon luminosities of \( L_\gamma \simeq 7.8 \times 10^{39} \text{ erg s}^{-1} \) and \( 1.9 \times 10^{39} \text{ erg s}^{-1} \) for the southern and northern lobes, respectively. In agreement with our model, the \( \gamma \)-ray flux counterparts from the hadronic interactions can be estimated as follows. The photopion efficiency for \( \text{He} \) nuclei inside the giant lobes is \( 7.8 \times 10^{-3} \) when the buoyancy arguments are considered, and \( 4.0 \times 10^{-4} \) and \( 8.4 \times 10^{-4} \) when spectral arguments are taken into account for the southern and northern lobes, respectively. Using the previous values of photopion efficiencies and the CR luminosities at \( \sim 1 \text{ TeV} \) reported in Table 2, the photon luminosities are calculated and reported in Table 3. Values reported in Table 3 without (with) round parenthesis are calculated considering the ages of the giant lobes estimated by buoyancy (spectral) arguments. Using the timescales for this hadronic process, the CR luminosities at 1 TeV (see Table 2) and the values reported in the literature (see Table 1), the total and CR energies as well as the total pressure in the giant lobes are reported in Table 3. The values reported in this table for \( \alpha_A \sim 2.5 \) and the ages of the lobes based on the spectral arguments are in accordance with those reported by Abdo et al. (2010a); Harcastle et al. (2009); Fraija (2014). Therefore, the \( \gamma \)-ray flux coming from pion decay product can contribute to the \( \gamma \)-ray flux reported by Abdo et al. (2010a) for \( \alpha_A \sim 2.4 \) and 2.5 - 2.6 when the buoyancy and spectral arguments are considered, respectively.

In order to describe the spectral energy distribution (SED) of the north and south lobes, the lepto-hadronic model showed in Fraija (2014) is used for accelerating CRs. Figure 5 shows the fit of the SED of the north (left panel) and south (right panel) lobes. The Wilkinson Microwave Anisotropy Probe data (WMAP; Hinshaw et al. 2009; Page et al. 2003) at radio wavelengths (22 to 94 GHz) are described with synchrotron emission. The Fermi-LAT data (Abdo et al. 2010a) are interpreted as the superposition of inverse Compton (CMB and EBL) and hadronic interactions. The typical CMB and EBL fluxes and photon energies were used from Dermer (2013), and the values of electron Lorentz factors from Fraija (2014). The contribution of pion decay products from hadronic interactions were calculated considering the photopion efficiency based on spectral arguments and the CR luminosities normalized with the UHECRs and extrapolated to energies as low as 1 TeV. In addition, we consider the photon indexes reported by Fermi-LAT instrument; \( 2.5^{+0.1}_{-0.2} \) for the north lobe and \( 2.6^{+0.14}_{-0.15} \) for the south lobe which correspond to the CR luminosities of \( L_\gamma = 4.12^{+0.28}_{-0.30} \times 10^{43} \text{ erg s}^{-1} \) for the north and \( 1.87^{+0.11}_{-0.13} \times 10^{43} \text{ erg s}^{-1} \) for south lobe. Figure 5 displays that the hadronic interactions from ultra-relativistic CR normalized with the UHECRs around the lobes of Cen A are consistent with GeV \( \gamma \)-ray flux when the photopion product efficiency for \( \text{He} \) nuclei is used.

6. PEV NEUTRINO ANALYSIS IN THE LOBES

PeV neutrino events from the H.E.S.E catalog (IC14, IC20 and IC35) reported by the IceCube Collaboration together with circular regions of 15° in the boundaries of the PeV events are shown in Figure 6. This figure shows that the maximum UHECRs inside the median angular error of these PeV neutrinos are: IC14 is associated with 2 events in a circle centered at \( \sim (\text{DEC}:-15°, \text{R.A.}:-6°) \), IC20 is associated with 2 events in a circle centered at \( \sim (\text{DEC}:-90°, \text{R.A.}:-52°) \) and IC35 is associated with 10 events in a circle centered at \( \sim (\text{DEC}:-41°, \text{R.A.}:-15°) \). Therefore, the UHECR events inside the region centered at \( \sim (\text{DEC}:-41°, \text{R.A.}:-15°) \) could be linked with IC35 neutrino. Figure 7 shows that IC35 event is inside and also around the boundaries of the circular regions of 15° centered in the southern giant lobe and Cen A, respectively. Therefore, due to the IC35 event would be outside of the circular region of 15° centered in the northern giant lobe, the southern giant lobe will only be considered to explain this neutrino event. In this case, the number of UHECRs associated to both the southern giant lobe and the IC 35 event is 10 and then, the CR luminosity linked to these events are 0.7 times those reported in Table 2. In order to explain the IC35 event, the \( \text{He} \) nuclei are assumed at an energy of \( \sim 100 \text{ PeV} \) and the accelerated and diffusion timescales are calculated. 100-PeV \( \text{He} \) nuclei are accelerated in a timescale of \( t_{\text{He,acc}} \sim 2.1 \times 10^4 \text{ Myr} \), and then they diffuse through the giant lobes and escape in a timescale of \( t_{\text{He,esc}} \sim 7.2 \times 10^2 \text{ Myr} \). By comparing the escape timescale of the 100-PeV \( \text{He} \) nuclei with the ages of the giant lobes (using the buoyancy and spectral arguments), it can be noticed that \( \text{He} \) nuclei cannot escape from the giant lobes if their ages are obtained by spectral arguments. Otherwise, they could escape only when the ages are those estimated by the buoyancy arguments. Hereafter, the ages of the giant lobes estimated by the buoyancy arguments will be considered. We consider the hadronic interactions inside and outside the lobes. The hadronic interactions in the inner and giant lobes will be analyzed.

Giant lobes — \( \text{He} \) nuclei with energies less than \( \sim 90 \text{ EeV} \) as shown in eqs. (18) and (19) interact within the giant lobes with an average density proton of \( n_p = 10^{-4} \text{ cm}^{-3} \) (see Table 4). In this case, the efficiency of photopion is \( 5.3 \times 10^{-3} \), and therefore, the number of events is much less than one, as shown through the two-dotted-dashed magenta line in Figure 8. This line in each panel displays the number of events as a function of the power index of \( \text{He} \)-nuclei spectrum for \( \alpha_\gamma = 2.2, 2.3, 2.4 \) and 2.5. The maximum number of \( \sim 2 \text{-PeV} \) neutrinos expected from the southern giant lobes when hadronic interactions between \( \text{He} \) nuclei and protons are considered is \( \sim 0.08 \) for \( \alpha_\gamma = 2.8 \).

100-PeV \( \text{He} \) nuclei in the direction of the IC35 event interact with CMB and EBL photons. For the photo-hadronic interactions with EBL photons, we take into account the infrared (IR), optical and ultraviolet (UV) photon densities which are \( 6.3 \times 10^{-1} \text{ cm}^{-3} \), \( 2.1 \times 10^{-2} \text{ cm}^{-3} \) and \( 3.2 \times 10^{-4} \text{ cm}^{-3} \) for \( \epsilon_{\gamma,br} \approx 10^{-2}, 1 \) and 4 eV (see eq. 11), respectively. Due to ultra-relativistic \( \text{He} \) nuclei interacting with CMB photons \( (\epsilon_{\gamma,br} \approx 2.3 \times 10^{-4} \text{ eV}) \) peak at \( \sim \text{EeV} \) (e.g. Fraija & Marinelli 2016), these interactions will not be considered. Dashed blue line in Figure 8 shows the number of events as a function of power index of \( \text{He} \) nuclei spectrum when IR photons are considered for \( \alpha_\gamma = 2.2, 2.3, 2.4 \) and 2.5. In this case, the maximum number of events expected is \( 4 \times 10^{-3} \) for \( \alpha_\gamma = 2.8 \). The numbers of neutrino events from the p\( \gamma \) interactions with UV and optical photons are not shown in this figure because these are much less than \( 10^{-5} \).

Inner lobes — Analysis of the Chandra/ACIS-I and XMM-Newton observations of X-ray emission from the inner lobes and ambient medium showed an X-ray filament consisted of five spatially resolved X-ray knots in the northern radio lobe (Kraft et al. 2009) and a bright X-ray enhancement along the edge of southwest radio lobe (Kraft et al. 2003, 2007).
The origin of the X-ray knots were explained as the result of cold gas heated by a direct interaction with the jet. The X-ray emission along the edge of the southwest radio lobe was modelled as a thin and hot shell X-ray emitting plasma. Due to the temperature and density of the gas in the hot shell is much higher than the ambient medium, then the inflation of the southwest radio lobe is driving a strong shock into ambient medium. Table 4 shows the densities and lifetime of the knots, the hot shell and the ambient medium in the northern and southwest inner lobes, respectively.

| Parameters | North | South |
|------------|-------|-------|
| Density Lifetime Photopion Efficiency | 2.2 | 2.6 | 2.2 | 2.6 |
| $\gamma$-ray luminosity ($\times 10^{44}$ erg/s) | $L_\gamma$ | $8.4 \times 10^{-2}$ (9.2 x $10^{-3}$) | $5.2$ (48.4) | $8.4 \times 10^{-4}$ (4.4 x $10^{-5}$) | $0.6$ (48.4) |
| Pressure ($\times 10^{-13}$ dyn cm$^{-2}$) | $P_{\text{He}}$ | $0.5$ (2.0 x $10^{-1}$) | $1.9 \times 10^5$ (18.3) | $1.1$ (1.8 x $10^{-3}$) | $52.6$ (9.1) |
| Total energy ($\times 10^{58}$ erg) | $E_{\text{tot}}$ | $0.6$ (2.4 x $10^{-3}$) | $2.4 \times 10^2$ (22.5) | $1.4$ (2.3 x $10^{-1}$) | $64.8$ (11.1) |
| CR energy ($\times 10^{56}$ erg) | $E_A$ | $0.5$ (3.9 x $10^{-2}$) | $2.4 \times 10^2$ (22.3) | $1.3$ (1.9 x $10^{-2}$) | $64.7$ (10.9) |

Notes:
- $^a$ This value is reported considering the cooling time for the hot ambient medium in the central regions of elliptical galaxies.
- $^b$ Region located in the northern inner Lobe.
- $^c$ Region located in the southwest inner Lobe.

References: Kraft et al. (2009); Kraft et al. (2003, 2007); Croston et al. (2009)

Taking into account the radii of inner lobes $\sim 10$ kpc (Kraft et al. 2003, 2007), the maximum He-nuclei energy reached by stochastic processes inside the inner lobes is $\sim 18$ EeV. Therefore, the acceleration and the diffusion timescales for 18-EeV He nuclei are $t_{\text{He,esc}} \sim 3 \times 10^{-2}$ Myr and $t_{\text{He,esc}} \sim 5 \times 10^{-2}$ Myr. For the inner lobes luminosities cannot be normalized with the UHECRs found around the IC35 event due to the ample discrepancy between the maximum energy that ultra-relativistic He nuclei reached in the inner lobes and the minimum UHECR detected by PAO. Due to both timescales are similar $t_{\text{He,acc}} \sim t_{\text{He,esc}}$. The acceleration timescale of $t_{\text{He,acc}} \sim 2.1 \times 10^{-4}$ Myr and the diffusion timescale of $t_{\text{He,esc}} \simeq 7.2 \times 10^2$ Myr for 100-GeV He nuclei were calculated. Our analysis is divided for the northern and southwest inner lobes.

- Northern inner lobe. The acceleration and diffusion timescales of He nuclei and the lifetimes of knots, $t_{\text{He,acc}} \ll t_{\text{lt,k}} \ll t_{\text{He,esc}}$, indicate that these nuclei can be accelerated but cannot escape from the knots. Here, $t_{\text{lt,k}}$ is used to define the lifetime of the knots. Taking into account the thermal density, the photopion production efficiency lies in the range of $1.7 \times 10^{-3} \leq t_{\text{He,p}} \leq 3.9 \times 10^{-3}$ (see Table 3). In this case, unrealistic luminosities larger than $> 10^{44}$ erg/s at 100 PeV are necessary to produce a 2-PeV neutrino event.

- Southwest inner lobe. Similarly, the timescales $t_{\text{He,acc}} \ll t_{\text{lt,s}} \ll t_{\text{He,esc}}$, show that these nuclei can be accelerated up $\sim 100$ PeV but cannot escape from the hot shell and the ambient medium. Here, $t_{\text{lt,s}}$ is used to define the lifetime of the hot shell and the ambient medium. Considering the thermal density of the hot shell and the ambient medium, the photopion production efficiency lies in the range of $4.1 \times 10^{-3} \leq t_{\text{He,p}} \leq 1.8 \times 10^{-2}$ (see Table 3). Similarly, for this inner lobe unrealistic luminosities again larger than $> 10^{44}$ erg/s at 100 PeV are necessary to produce a 2-PeV neutrino event.

7. Analysis of Neutrinos and UHECRs from the Core Emission

Close to the core, Cen A has been observed from radio wavelengths to TeV $\gamma$-ray energies. The broadband SED of Cen A presents a double-humped shape; the lower energy hump has a peak located at $10^{-2}$ eV and the second hump at hundreds of keV. Recently, Fraija & Marinelli (2016) presented a lepto-hadronic model to describe the broadband SED of the closest radio galaxies; from radio to sub-GeV photons as one-zone SSC model and the observed TeV $\gamma$-ray spectrum as photon-hadronic interaction. The best-fit parameters reported after describing successfully the SED of Cen A were: the Doppler factor $\delta_d \sim 1.0$, the size of emitting region $r_d \sim 5.2 \times 10^{15}$ cm and the strength of the magnetic field $B \sim 3.6$ G. In addition, they computed that ultra-relativistic protons confined at the emitting region can be accelerated up to $E_{\text{max}} = 40$ TeV. Therefore, it is worth noting that although ultra-relativistic protons cannot be accelerated larger than 40 EeV close to the core at the emitting region, they might be accelerated during the flaring intervals (see eq. 17) and/or partially in the giant lobes. It is very interesting the idea that UHECRs could be accelerated not totally in the jet, in part in the jet and in part in the lobes ($> 4 \times 10^{19}$ eV). Therefore, in order to reproduce the 2-PeV neutrino event we consider as photon targets those radiated by synchrotron radiation from the core emission of Cen A, and in particular the photon flux at $\sim 4$ eV. At this energy, the observed flux and photon density are $F_{\text{ph}} \sim 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $n \sim \delta_d^2 F_{\text{ph}} \eta_j^2 F_{\text{ph}}$, respectively, and then the photopion efficiency becomes $2.8 \times 10^{-3}$. Supposing that UHE He nuclei could have been accelerated together with protons close to the core emission and then, using the CR luminosities reported in Table 2, the number estimated of PeV-neutrino events as a function of power index of
He nuclei spectrum for $\alpha_\nu = 2.2, 2.3, 2.4$ and 2.5 is plotted, as shown in Figure 8. Dotted orange line shows the number of events created by the photo-hadronic interactions with the synchrotron photons close to the core. This line displays that the number of events is much less than one. This result is similar to that found by Saba et al. (2013) who used the $\gamma$-ray flux detected by Fermi-LAT to estimate the number of neutrinos from Cen A

8. INTERACTIONS OUTSIDE CEN A

Considering the diffusion timescale and the ages of the giant lobes, He nuclei with energies less than 100 PeV can hardly escape from the lobes and interact out of them. Therefore, neutrinos with energies less than 2 PeV cannot be expected outside the giant lobes. On the other hand, He nuclei with energies larger than ~ 100 PeV can escape from the giant lobes and interact around them. Once these ultra-relativistic He nuclei abandon the giant lobes and are directed towards the Earth, they can interact in their path to Earth (in our galaxy or out of it). The optical depths for these hadronic interactions in their paths to Earth are

$$\tau \simeq 8.4 \times 10^{-2} \left( \frac{n_p}{\text{cm}^{-3}} \right) \left( \frac{l}{100 \text{kpc}} \right).$$

Here, $l$ is the average distance where the interactions occur. Considering the average distance of ~ 4 Mpc between Cen A and Earth with density $\sim 10^{-3}$ cm$^{-3}$, the optical depth becomes $3.5 \times 10^{-3}$. Similarly, considering the average radius of our galaxy of 20 kpc with density of ~ 1 cm$^{-3}$ (Kalberla & Kerp 2009), the optical depth is $\sim 10^{-2}$. Therefore, the probability so that UHE He nuclei interact outside or/and inside our galaxy is very low.

Figure 9 shows the Galaxies located at distances less than ~ 4 Mpc and around the lobes of Cen A and the IC35 event. Assuming that UHE He nuclei could arrive and introduce inside these galaxies, the photopion efficiency is calculated through the hadronic cooling and diffuse timescales. In this case, the efficiency can be written as

$$f_{\text{He}} = 1 - \exp(-t_{\text{He, esc}}/t_{\text{He p}})$$

where $t_{\text{He p}} \simeq \sigma_{\text{He p}} n_p$. Using the relation between the gas contained in a galaxy and the star-formation rate which is given by (Kennicutt 1998)

$$\Sigma_{\text{SFR}} = A_{\text{SFR}} \left( \frac{\Sigma_{\text{gas}}}{1 \text{M}_\odot \text{pc}^{-2}} \right)^{\alpha_k} \text{M}_\odot \text{yr}^{-1} \text{kpc}^{-2},$$

with $(A_{\text{SFR}}, \alpha_k) = (2.5 \pm 0.7 \times 10^{-4}, 1.4 \pm 0.15)$, we can estimate the gas density in the case of Dwarf Irregular (dIrr) galaxies inside a radius $\sim 1$ kpc for a height $\sim 500$ pc. In this case, the density can be written as

$$n_g \simeq 24 \left( \frac{\text{SFR}}{\text{M}_\odot \text{yr}^{-1}} \right)^{0.71} \left( \frac{R}{\text{kpc}} \right)^{-1.43} \left( \frac{l}{500 \text{pc}} \right)^{-1} \text{cm}^{-3}.$$

It is worth noting that in the case of Dwarf Elliptic (dE) galaxies, a same upper limit of gas density can be used (Bouchard et al. 2007).

Table 5 shows the Galaxies located at distances less than ~ 4 Mpc and around the lobes and the IC35 event. This table exhibits the name of galaxies (column 1), type (column 2), the density (column 3), magnetic field (column 4), interaction timescale (column 5) and diffusion time (column 6) associated to them. These Galaxies in general are dE-type that are gas-poor and dIrr-type that are gas-rich. The strengths of the magnetic field were calculated using (Thompson et al. 2006)

$$B \simeq 5.64 \mu G \left( \frac{n_g}{\text{cm}^{-3}} \right)^{0.7} \left( \frac{l}{500 \text{pc}} \right)^{0.7}.$$
energy of \( \sim 170 \) TeV and a redshift of 0.001, the value of optical depth is \( \tau_{\gamma\gamma}=10 \). Therefore, photons with energies larger than \( \sim 100 \) TeV created at \( \sim 4 \) Mpc are completely attenuated by the EBL without reaching the Earth. For our case, when the 2-PeV neutrino is created by hadronic interactions around the Galaxies ESO324-G024 and NGC4945, photons at PeV energies are absorbed in their path to Earth. In other words, a 2-PeV neutrino can be detected on Earth without observing its electromagnetic counterpart (Franceschini et al. 2008). It is worth emphasizing that \( \gamma \)-ray fluxes at TeV energies are very low (undetectable) due to that the relativistic He nuclei less than \( \sim 100 \) PeV can hardly escape from the lobes and therefore cannot interact out of them. The counterpart of \( \gamma \)-ray flux at 4 PeV created by neutral decay products together with 2-PeV neutrino would fall in more than four order of magnitude at energies of 4 TeV, being low enough to be detectable.

Due to IC35 event is outside of the circular window of \( 15^\circ \) around northern giant lobe, the previous analysis was done for the southern giant lobe. However, considering a radius of \( 15^\circ \) around the north giant lobe, two neutrino events IC48 and IC49 with energies 104.7\(^{+13.5}_{-10.2} \) TeV and 59.9\(^{+8.3}_{-7.9} \), respectively, could be spatially correlated with this lobe. In this model, these events would be produced by relativistic He nuclei with energies of \( \sim 6 \) and 3 PeV, respectively. Therefore, these relativistic He nuclei would escape from the north giant lobes in timescales of tens of Gyr, that are much larger than the ages of the lobe. The previous result indicates that the neutrino events IC48 and IC49 could not have been created around the northern giant lobe.

9. Conclusions

The analysis done in this paper has been based on the PeV-neutrino event (IC35) reported in the HESE catalog, the lobes of Cen A, UHECRs collected by PAO between 2004 January 1\(^{th}\) and 2014 March 31.

In this paper has been discussed: i) the maximum energy that nuclei can reached in the giant lobes with their timescales, ii) the average deflecting angles that nuclei can undergo due to galactic magnetic fields on the galactic plane, and in the halo and also due to extragalactic magnetic field, iii) the magnetic-field luminosity condition of UHECRs in the lobes and iv) the energy-loss mean free path for photodisintegration processes. It is shown that inside a radius of \( \sim 15^\circ \) centered around the radio galaxy Cen A, UHE helium nuclei are the most promising candidates, UHE nitrogen nuclei could contribute with a small fraction and UHE iron nuclei and protons are excluded which agree with the results recently reported by Aab et al. (2014) about the UHECR composition at the highest energies. Similarly, a possible correlation between the degree of anisotropy in a particular direction and the chemical composition is expected for UHECR events collected to distances less than \( \lesssim 75 - 100 \) Mpc.

Considering a circular windows of radius \( 15^\circ \) centered on Cen A, 14 events were found, and then using a simple power law the UHECR luminosities normalized with these events were reported. With the values of parameters reported in the literature, we have showed some acceleration mechanisms that could accelerate nuclei inside the lobes up to energies as high as \( 10^{20} \) eV. Taking into consideration the CR luminosity extrapolated at 1 TeV we have described the faint \( \gamma \)-ray fluxes reported by the Fermi Collaboration assuming relativistic He nuclei.

Focusing on the southern giant lobe, 10 events were found inside the region demarcated by the circular window of radius \( 15^\circ \) around this giant lobe and the median angular error of the IC35 event. By normalizing the luminosity with these events, the number of neutrinos were computing through photohadronic and hadronic interactions inside and outside the lobes, assuming He nuclei. The effective area in the Cen A declination was used. We showed that although hadronic interactions are a more efficient process than photohadronic interactions, none of them can generate a 2-PeV neutrino inside the inner and/or giant lobes. Otherwise, ultra-relativistic He nuclei interacting outside the giant lobes in their path to Earth with the Galaxies ESO324-G024 and NGC4945 could generate a 2-PeV neutrino for a power law of \( \alpha_{He} \sim 2.4 - 2.5 \). The value of the He-nuclei spectral index could be higher if the particle density in the Galaxies or He-nuclei luminosity at 100 PeV would be less to that estimated. This is the case, if we consider a small fraction of light nuclei in the UHECR composition. This result indicates that if hadronic interactions occurred between the southern giant lobe and Earth with the CR luminosity normalized at 100 PeV with the UHECRs in the direction of Cen A, a 2-PeV neutrino event could be created, being consistent with the IC35 event reported in the HESE catalog. Finally, it is important to highlight that the increasing statistics by the IceCube neutrino telescope and PAO will provide more evidence of our scenario. If this model is correct, from two to three UHECRs and a 2-PeV neutrino would be expected in PAO and IceCube experiments, respectively, during the following four years.

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Fig. 1.— Poisson test at different angular distances from Cen A. Black circles are the $p$-values (probability of cosmic ray counts around Cen A at least as large as observed, if the cosmic rays are uniformly distributed). The red line corresponds to the value of significance of the test, $\alpha = 0.001$; points below the line indicate $p$-values that are significantly different from the expected values if the null hypothesis holds.

Fig. 2.— Effective area of electron, muon and tau neutrino for a point-like source in the declination of Cen A.
Fig. 3.— Energy-loss mean free path of UHECR proton and ions (He, N and Fe) due to interactions with CMB photons.

Fig. 4.— Sky-map with 231 UHECRs collected by PAO (red crosses; Aab et al. 2015) and the Lobes of Cen A (black point).
Fig. 5.— Fits of the SED of the north (left) and south (right) lobes. We use synchrotron emission to describe WMAP data and IC/CMB, IC/EBL and hadronic interactions to model LAT data.

Fig. 6.— Sky-map with PeV neutrino events detected by IceCube (HESE catalog; blue triangles) and 231 UHECRs collected by PAO (red crosses; Aab et al. 2015).
Fig. 7.— Sky-map with 54 neutrino events detected by IceCube (HESE catalog\textsuperscript{a}; blue triangles), 231 UHECRs collected by PAO (red crosses; Aab et al. 2015) and the Lobes of Cen A (black point)
\textsuperscript{a}http://icecube.wisc.edu/science/data/HE-nu-2010-2014

Fig. 8.— Number of 2-PeV neutrino events as a function of He-nuclei and neutrino spectral indexes. This figure shows the neutrino contribution produced by ultra-relativistic He nuclei interacting with Galaxies (ESO324-G024 and NGC4945) in the path to Earth (dot-dashed green line), with thermal density inside the giant lobes (double dot-dashed magenta line), with synchrotron photons close to the core (dotted orange line) and with IR photons (dashed blue line).
Fig. 9.— The closest Galaxies located at distances less than $\sim 4$ Mpc and around the lobes of Cen A and the IC35 event.