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Hadronic processes as origin of TeV emission in Fanaroff-Riley Class I: Cen A, M87 and NGC1275

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Recent detections of Fanaroff-Riley Class I AGNs by HESS, MAGIC, and VERITAS suggest that very-high-energy γ-rays (VHE, E$\geq$100 GeV) may not have a leptonic origin. We present a hadronic model to describe the TeV photons as the neutral pion decay resulting from pγ and pp interactions. For the pγ interaction, we assume that the target photons are produced by leptonic processes and apparent at the second spectral peak. For the pp interaction we consider as targets the thermal particle densities in the lobes. We show that this model can describe the TeV spectra of the radio galaxies NCG 1275, M87 and Cen A.

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Fanaroff & Riley Class I (FRI) sources are radio loud active galactic nuclei (AGNs) exhibiting clear structure of a compact central source, twin large-scale jets and lobes. The spectra of FRI radio galaxies are generally well described by standard non-thermal Synchrotron and Synchrotron-Self Compton (SSC) models [1, 2, 3]. The radio through optical emission originates from synchrotron radiation while the X-ray through γ-ray emission originates from SSC. A leptonic model with only one population of electrons predicts a spectral energy distribution (SED) that can not extend to $\geq 10^{23}$ Hz [4, 5]. Also, some authors have suggested that the GeV to TeV emission may have origins in different physical processes [7]. Therefore, we use these two facts and consider hadronic processes (pp and pγ) to describe the VHE spectra of Cen A [2, 3, 6], M87 [8, 9] and NGC1275[10, 11]. We first require a description of the SED up to MeV/GeV [2, 3, 8, 10]. Then, we assume the thermal particle densities in the lobes and the lobe's distance to the core [12, 13] to describe the TeV energy contribution to the spectrum either by pγ or pp interaction.

NGC 1275 is located at the centre of the Perseus cluster at a redshift of $z = 0.0179$. It has a strong, compact nucleus and jet. Its jet has been detected with an intrinsic velocity of $0.3c - 0.5c$ and oriented at an angle of $\approx 30^\circ$ - 55° to the line of sight [10]. M87 is located in the Virgo cluster of galaxies at a distance of $\sim$ 16 Mpc (z=0.0043). It has been detected from radio to VHE gamma rays. In particular, it was detected by HESS, MAGIC and VERITAS showing a variable TeV emission on timescales of years [8], although much faster variations, down to timescales of a day and less, have been observed [14, 15]. Cen A is at a distance of 3.8 Mpc. Its giant radio lobes, which subtend $\sim 10^\circ$ on the sky, are oriented primarily in the north-south direction. Also, Cen A has a jet with an axis subtending an angle to the line of sight estimated as $15^\circ - 80^\circ$ [2, 3].

1. Hadronic interactions

We assume for protons a power law injection spectrum given by $dN_p/dE_p = A_p E_p^{-\alpha_p}$, where α_p is the spectral index and A_p is the proportionality constant.

We assume that the pγ interaction takes place when accelerated protons collide with target photons [16] originated in the SSC process. Then, the energy loss rate due to pion production is given by $t'_{p,\gamma} = 1/(2\gamma_p)\int_{\varepsilon_0}^{\infty} d\varepsilon\, \delta_\pi(\varepsilon)\xi(\varepsilon)\,\varepsilon \int_{\varepsilon/2\gamma_p}^{\infty} dx x^{-2} n(x)$ [17], where $n(x) = dn_\gamma/d\varepsilon_\gamma(\varepsilon_\gamma = x)$, $\sigma_\pi(\varepsilon)$ is the cross section for pion production for a photon with energy ε in the proton rest frame, $\xi(\varepsilon)$ is the average fraction of energy transfered to the pion, $\varepsilon_0 = 0.15$ is the threshold energy and, $\gamma_p = \varepsilon_p/m_p^2$. The fraction of energy lost is $f_{\pi^0,p\gamma} \approx t'_d/t'_{p,\gamma}$, (where $t'_d \sim r_d/\Gamma$ is the expansion time scale) and the differential spectrum, dN_γ/dE_γ, of the photon-pions produced by pγ interaction is given by,

$$\left(E^2\frac{dN}{dE}\right)^{obs}_{\pi^0-\gamma} = A_{p,\gamma}\begin{cases}\left(\frac{E^{obs}_{\pi^0-\gamma,c}}{E_0}\right)^{-1}\left(\frac{E^{obs}_\gamma}{E_0}\right)^{-\alpha_p+3} & E^{obs}_\gamma < E^{obs}_{\pi^0-\gamma,c}\\ \left(\frac{E^{obs}_\gamma}{E_0}\right)^{-\alpha_p+2} & E^{obs}_{\pi^0-\gamma,c} < E^{obs}_\gamma\end{cases} \tag{1.1}$$

where

$$A_{p,\gamma} \propto \delta_D^{\alpha_p} E_0^2 A_p\, e^{-\tau_{\gamma\gamma}}(1+z)^{-\alpha_p} E^{obs\,-1}_{\gamma,c} L^{obs} dt^{obs} d_z^{-2} \tag{1.2}$$

and

$$E^{obs}_{\pi^0-\gamma,c} = 5\times10^{-2}\,\frac{\delta_D^2\,(m_\Delta^2-m_p^2)}{(1+z)^2(1-cos\theta)}\,E^{obs\,-1}_{\gamma,c} \tag{1.3}$$

where L^{obs} is the observed luminosity, dt^{obs} is the observed variability, $\tau_{\gamma\gamma}$ is the optical depth [3], δ_D is the Doppler factor and d_z is the distance to the source.

On the other hand, for pp interactions we assume that the accelerated protons collide with thermal particles in the giants lobes. Then, the energy loss rate due to pion production is given by $t'_{pp} = (n'_p\,k_{pp}\,\sigma_{pp})^{-1}$[16], where $\sigma_{pp} = 30$ mbarn is the nuclear interaction cross section, $k_{pp} = 0.5$ is the inelasticity coefficient and n'_p is the comoving thermal particle density. The fraction of energy lost by pp is $f_{\pi^0,pp} \approx t'_d/t'_{pp}$ and the differential spectrum of the photon-pions produced by pp interaction, dN_γ/dE_γ, is given by,

$$\left(E^2\,\frac{dN}{dE}\right)^{obs}_{pp,\gamma} = A_{pp}\,\left(\frac{E^{obs}_\gamma}{E_0}\right)^{2-\alpha_p} \tag{1.4}$$

with,

$$A_{pp} \propto \frac{\Gamma^2\,\delta_D^{2+\alpha_p}\,E_0^2\,A_p\,e^{-\tau_{\gamma\gamma}}}{(1+z)^{2+\alpha_p}}\,R\,n_p\,dt^{obs\,2}\,d_z^{-2} \tag{1.5}$$

where n_p is the thermal particle density, R is the distance to the lobes from the AGN core and Γ is the bulk Lorentz factor. The eqs. 1.1 and 1.4 represent the TeV energy range contribution to the spectrum. We have considered only one hadronic interaction at once.

The input parameters used to fit the leptonic contribution to the SED of Cen A [2, 3], M87 [8] and NGC1275[8] are shown in Table 1. In Table 2 the parameters used and their values to describe the TeV contribution to the spectrum considering pγ or pp interactions are shown.

Parameters	Cen A	M87	NGC1275
dt^{obs} (s)	2.5×10^6	1.0×10^5	3.17×10^7
L^{obs} (erg s^{-1})	5×10^{43}	1.0×10^{44}	6×10^{43}
θ (degrees)	40	10	20
δ_d	1.47	3.9	2.9
d_z (pc)	3.8	16	76

Table 1. Input parameters used to fit the leptonic contribution of the SED

Parameters	Cen A	M87	NGC1275	Parameters	Cen A	M87	NGC1275
α_p	2.82	2.49	2.7	α_p	2.82	2.49	2.7
$E^{obs}_{\pi^0-\gamma,c}$ (GeV)	317.1	674.9	80,6	$n_p(cm^{-3})$	10^{-4}	10^{-1}	10^{-1}
$A_{p\gamma}$ (MeV cm^2 s)$^{-1}$	1.37×10^{-2}	5.37	4.37×10^2	A_{pp} (MeV cm^2 s)$^{-1}$	5.9×10^{-13}	2.0×10^{-14}	7.2×10^{-14}
E_0 (TeV)	1	1	1	E_0 (TeV)	1	1	1
				R (kpc)	100	150	200

Table 2. Parameters used to describe the TeV spectrum considering pγ (left) or pp (right) interactions are shown. [13]

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2. Discussion and Conclusions

When pγ interaction is considered and assuming that each photon-pion carries $\sim$ 10%, we obtain a broken-power law (eq. 1.1) with break energies inside the energy range and spectral indexes observed by HESS, VERITAS and MAGIC detections of Cen A, M87 and NGC1275 respectively. When pp interaction is considered and assuming that each pion carries $\sim$ 18% and splits in two $\gamma-$rays, we also obtain energy ranges observed by the HESS, VERITAS and MAGIC. For Cen A the number density of thermal particles in the giants lobes and the distance lobes-core are known, Hardcastle et al. (2009). However for the M87 and NGC1275, these values are not well-determined. Fraija et al. (2012) shows the proportionality constant (App) as a function of distance to the core (R) for typical number density of thermal particles (n_p), obtaining the minimum App values for this process.

We observe that pγ interaction is much stronger that pp interaction. For Cen A, the extrapolation to ultra-high energies (UHE) of the proton spectrum could explain the observed UHE cosmic rays (UHECR) observed by the Auger Observatory [3] only for case when pp interactions are the responsibles of the TeV emission . Otherwise the expected number of UHECR obtained is several orders of magnitude above the observations. We have taken into account the variability for M87, $\sim 10^5$ s, that corresponds to low state, for short timescale variations presented in flaring state this model cannot be accommodated.

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