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Emission processes and Ultra High Energy Cosmic Rays from NGC1275?

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ABSTRACT
Long gamma-ray bursts have been widely associated with collapsing massive stars in the framework of collapsar model. High-energy neutrinos and photons can be produced in the internal shocks of middle relativistic jets from core-collapse supernova. Although photons can hardly escape, high-energy neutrinos could be the only signature when the jets are hidden. We show that using suitable parameters, high-energy neutrinos in GeV - PeV range can be produced in the hidden jet inside the collapsar, thus demonstrating that these objects are candidates to produce neutrinos with energies between 1 - 10 PeV which were observed with IceCube. On the other hand, due to matter effects, high-energy neutrinos may oscillate resonantly from one flavor to another before leaving the star. Using two (solar, atmospheric and accelerator parameters) and three neutrino mixing, we study the possibility of resonant oscillation for these neutrinos created in internal shocks. Also we compute the probabilities of neutrino oscillations in the matter at different distances along the jet (before leaving the star) and after in vacuum, on their path to Earth. Finally, neutrino flavor ratios on Earth are estimated.

Key words: Long Gamma-ray burst: High-energy Neutrinos: – Neutrino Oscillation

1 INTRODUCTION

NGC 1275, also known as Perseus A and 3C 84, is the nearby active galaxy located at the centre of the Perseus cluster at redshift of $z = 0.0179$. This source has a strong, compact nucleus which has been studied in detail with very long baseline interferometry (VLBI)**????**. These observations reveal a compact core and a bowshock-like souther jet component moving steadily outwards at 0.3 mas/year **??**. The norther counter jet is also detected, though it is much less prominent due to Doppler dimming, as well as to free-free absorption due an intervening disk. Walker, Romney and Berson (1994) derive from these observations that the jet has an intrinsic velocity of $0.3c - 0.5c$ oriented at an angle $\approx 30^\circ$ - 55° to the line of sight. Polarization has recently been detected in the southern jet**?**, suggesting increasingly strong interactions of the jet with the surrounding environment**?**.
Perseus furthermore hosts a luminous radio mini halo - a diffuse synchrotron emission that fills a large fraction of the cluster core region - and shows a source extension of ≈200 kpc **?**. This radio mini-halo is well modeled by the hadronic scenario where the radio emitting electrons are produced in hadronic CR proton interaction with ambient gas protons requiring only a very modest fraction of few percent CR pressure relative to thermal pressure **?**. These conditions provide high target densities for hadronic CRp-p interactions and enhance the resulting γ-ray flux **?**. This source has been detected by MAGIC telescopes with a statistical significance of $6.6\,\sigma$ above 100 GeV in 46 hr of stereo observations carried out between August 2010 and February 2011. The measured differential energy spectrum between 70 GeV and 500 GeV can be described by a power law with a steep spectral index of $\Gamma = -4.1 \pm 0.7_{stat} \pm 0.3_{syst}$, and the average flux above 100 GeV is $F_\gamma = 1.3 \pm 0.2_{stat} \pm 0.3_{syst} \times 10^{-11}\, cm^{-2}\, s^{-1}$ **?**.

It has been proposed that astrophysical sources accelerating ultra high energy cosmic rays (UHECRs) also could produce high energy γ-rays by proton interactions with photons at the source and/or the surrounding radiation and matter. Hence, VHE photons detected from Cen A could be the result of hadronic interactions of cosmic rays accelerated by the jet with photons radiated inside the jet or protons in the lobes (**?????????**).

Pierre Auger Observatory (PAO) studied the spectra of UHECR above 57 EeV through their shower properties finding a mixed composition of p and Fe (**???**). By contrast, HiRes data are consistent with a dominant proton composition at those energies, but uncertainties in the shower properties (**?**) and in the particle physics extrapolated to this extreme energy scale (**?**) preclude definitive statements about the composition. At least two events of the UHECRs observed by PAO were detected (**??**) inside of a 3.1° circle centered at Cen A.

Synchrotron/Synchrotron-Self Compton (SSC) models have been very successful in explaining the multiwavelength emission from Broad-Line Lacertae (BL Lac) objects (**??**). If FRIs are misaligned BL Lac objects, then one would expect synchrotron/SSC

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to explain their non-thermal spectral energy distribution (SED) as well. In the synchrotron/SSC scenario the low energy emission, radio through optical, originates from synchrotron radiation while high energy emission, X-rays through VHE γ-rays, originates from SSC. However, many blazars have higher energy synchrotron peaks, so this mechanism then covers much of the X-ray band; for them only the γ-rays come from SSC mechanism. In Cen A, synchrotron/SSC model has been applied successfully to fit the two main peaks of the SED, jointly or separated, with one or more electron populations (**?????**). On the other hand, some authors (**???**) have considered hadronic processes to explain the VHE photons apparent in the SED.

In this work we use the fact that leptonic processes are insufficient to explain the entire spectrum of NGC1275, and introduce hadronic processes that may leave a signature in the number of UHECRs observed on Earth. Our contribution is to describe jointly the SED of NGC1275 as well as the observed number of UHECR by PAO. We first require a description of the SED up to the highest energies obtaining parameters as: proton spectral index (α_p), proton proportionality constant (A_p) and the normalization energy (E_0). Then, we use these parameters to estimate the expected UHECRs observed by PAO. The main assumption here, is the continuation of the proton spectrum to ultra high energies. We also estimate the neutrino expectation in a hypothetical Km^3 telescope when considering that the VHE photons in the SED of Cen A are produced by pp interaction.

2 JET DYNAMICS

3 LEPTONIC MODEL

3.1 Synchrotron self-Compton

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 broken power-law given by (**????**)

$$N_e(\gamma_e) = A_e \begin{cases} \gamma_e^{-\alpha} & \gamma_{e,m} < \gamma_e < \gamma_{e,b}, \\ \gamma_{e,b}\gamma_e^{-(\alpha+1)} & \gamma_{e,b} \leqslant \gamma_e < \gamma_{e,max}, \end{cases} \qquad (1)$$

where A_e is the proportionality electron constant, α 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 $U_B = B^2/8\pi$ and electrons $U_e = m_e \int \gamma_e N_e(\gamma_e) d\gamma_e$, the electron Lorentz factors are

$$\begin{aligned} \gamma_{e,m} &= \frac{(\alpha-2)}{m_e(\alpha-1)}\frac{U_e}{N_e} \\ \gamma_{e,b} &= \frac{3\,m_e}{4\,\sigma_T\beta^2}\,U_B^{-1}\,t_{syn}^{-1} \\ \gamma_{e,max} &= \left(\frac{9\,q_e^2}{8\pi\,\sigma_T^2\,\beta^4}\right)^{1/4} U_B^{-1/4}, \end{aligned} \qquad (2)$$

where the constants m_p, m_e, q_e and σ_T are the proton and electron mass, the electric charge and Thomson cross section, respectively, $\beta = v/c \sim 1$ and z=0.00183 is the redshift(**?**). The observed photon energies, $\epsilon_\gamma^{obs}(\gamma_e) = \sqrt{\frac{8\pi q_e^2}{m_e^2}}(1+z)^{-1}\,\delta_D\,U_B^{1/2}\,\gamma_{e,i}^2$, for each Lorentz factor (eq. 2) are

$$\begin{aligned} \epsilon_{\gamma,m}^{obs} &= \frac{\sqrt{8\pi}\,q_e(\alpha-2)^2}{m_e^3\,(\alpha-1)^2}\,(1+z)^{-1}\,\delta_D\,U_B^{1/2}\,U_e^2 N_e^{-2}, \\ \epsilon_{\gamma,c}^{obs} &= \frac{9\sqrt{2\pi}\,q_e\,m_e}{8\,\sigma_T^2\beta^4}(1+z)^{-1}\,\delta_D\,U_B^{-3/2}\,t_{syn}^{-2}, \\ \epsilon_{\gamma,max}^{obs} &= \frac{3\,q_e^2}{m_e\,\sigma_T\,\beta^2}(1+z)^{-1}\,\delta_D, \end{aligned} \qquad (3)$$

where we have applied the synchrotron cooling time scale,

$$t_{syn} = \frac{E_e'}{(dE_e/dt)'} = \frac{3m_e^2}{4\sigma_T\beta^2}U_B^{-1}\,E_e'^{-1} \qquad (4)$$

and δ_D is the Doppler factor. On the other hand, we have that the synchrotron spectrum is obtained by the shape of the electron spectrum (eq. 1) rather than the emission spectrum of a single particle. Therefore, the energy radiated in the range ϵ_γ to $\epsilon_\gamma + d\epsilon_\gamma$ is given by electrons between E_e and $E_e + dE_e$, then we can estimate the photon spectrum through emissivity $\epsilon_\gamma N_\gamma(\epsilon_\gamma) d\epsilon_\gamma = \left(-\frac{dE_e}{dt}\right) N_e(E_e) dE_e$. Following **?** and **?**, it is easy to show that if electron distribution has spectral indexes α and $(\alpha-1)$, then the photon distribution has spectral indexes $p = (\alpha-1)/2$ and $p = \alpha/2$, respectively. The proportionality constant is estimated 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 $P_{\nu,max}^{obs} \simeq \frac{dE/dt}{\epsilon_\gamma(\gamma_e)}$ and the distance D$_z$ from the source. Then, we can obtain the observed synchrotron spectrum as follow

$$\epsilon_\gamma^2 N_{\gamma,syn}(\epsilon_\gamma) = A_{syn,\gamma} \begin{cases} (\frac{\epsilon_\gamma}{\epsilon_{\gamma,m,syn}})^{4/3} & \epsilon_\gamma^{obs} < \epsilon_{\gamma,m,syn}^{obs}, \\ (\frac{\epsilon_\gamma}{\epsilon_{\gamma,m,syn}})^{-(\alpha-3)/2} & \epsilon_{\gamma,m,syn}^{obs} < \epsilon_\gamma^{obs} < \epsilon_{\gamma,c,syn}^{obs}, \\ (\frac{\epsilon_{\gamma,c,syn}}{\epsilon_{\gamma,m,syn}})^{-(\alpha-3)/2}(\frac{\epsilon_\gamma}{\epsilon_{\gamma,c,syn}})^{-(\alpha-2)/2}, & \epsilon_{\gamma,c,syn}^{obs} < \epsilon_\gamma^{obs} < \epsilon_{\gamma,max,syn}^{obs} \end{cases} \qquad (5)$$

where

$$A_{syn,\gamma} = \frac{P_{\nu,max}^{obs} n_e}{4\pi D_z^2}\,\epsilon_{\gamma,m}^{obs} \simeq \frac{8\pi\sigma_T\,\beta^2\,(\alpha-2)^2}{9\,m_e^2\,(\alpha-1)^2\,D_z^2}(1+z)^{-2}\,\delta_D^2\,U_B\,U_e^2\,N_e\,r_d^3 \qquad (6)$$

It is important to clarify that r_d is the region where emitting electrons are confined. Eq. 7 represents the peak at lower energies (radio wavelength) of the SED for each of the lobes.

$$\epsilon_\gamma^2 N_{\gamma,ssc}(\epsilon_\gamma) = A_{ssc,\gamma} \begin{cases} (\frac{\epsilon_\gamma}{\epsilon_{\gamma,m,ssc}})^{4/3} & \epsilon_\gamma^{obs} < \epsilon_{\gamma,m,ssc}^{obs}, \\ (\frac{\epsilon_\gamma}{\epsilon_{\gamma,m,ssc}})^{-(\alpha-3)/2} & \epsilon_{\gamma,m,ssc}^{obs} < \epsilon_\gamma^{obs} \\ (\frac{\epsilon_{\gamma,c,ssc}}{\epsilon_{\gamma,m,ssc}})^{-(\alpha-3)/2}(\frac{\epsilon_\gamma}{\epsilon_{\gamma,c,ssc}})^{-(\alpha-2)/2}, & \epsilon_{\gamma,c,ssc}^{obs} < \epsilon_\gamma^{obs} \end{cases}$$

4 HADRONIC MODEL

Some authors (**????**) have considered possible different mechanisms where protons up to ultra high energies can be accelerated. Thus, we suppose that Cen A is capable of accelerating protons up to ultra high energies with a power law injection spectrum (**?**),

$$\frac{dN_p}{dE_p} = A_p\,E_p^{-\alpha_p} \qquad (8)$$

where α_p is the proton spectral index and A_p is the proportionality constant. Energetic protons in the jet mainly lose energy by pγ and pp interactions (**?????**); as described in the following subsections.

4.1 pγ interaction

The pγ; interaction takes place when accelerated protons collide with target photons. The single-pion production channels are $p +$

$\gamma \to n + \pi^+$ and $p + \gamma \to p + \pi^0$, where the relevant pion decay chains are $\pi^0 \to 2\gamma$, $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$ and $\pi^- \to \mu^- + \bar{\nu}_\mu \to e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$ (**?**).

In this analysis we suppose that protons interact with SSC photons ($\sim$ 150 keV) in the same knot. If so, the optical depth is given as $\tau_{p,ssc} \approx r_d\, \theta_{jet}\, \Gamma\, n^{obs}_{\gamma ssc} \sigma_{p\gamma}$, where r_d is the value of the dissipation radius (**?**), θ_{jet} is the jet aperture angle, $\sigma_{p\gamma} = 0.9$ mbarn is the cross section for the production of the delta-resonance in proton-photon interactions and $n^{obs}_{\gamma ssc}$ is the particle density of SSC photons into the observer frame (**?**) given by,

$$n^{obs}_{\gamma ssc} \approx \frac{\epsilon_{knot}\, L^{obs}}{4\pi\, r_d^2\, E^{obs}_{\gamma,c}} \tag{9}$$

Assuming that the luminosity of a knot along the jet is a fraction $\epsilon_{knot} \approx 0.1$ of the observed luminosity $L^{obs} = 5 \times 10^{43}\, erg\, s^{-1}$ for $E^{obs}_{\gamma,c}$ keV, the optical depth is,

$$\tau_{p,ssc} \approx \Gamma^{-1} \left(\frac{\theta_{\rm jet}}{0.3}\right) \left(\frac{\epsilon_{\rm knot}}{0.1}\right) \left(\frac{L^{obs}}{6\times 10^{43}\,{\rm erg\,s^{-1}}}\right) \left(\frac{r_d}{10^{16}\,{\rm cm}}\right)^{-1} \left(\frac{E^{obs}_{\gamma,b}}{\rm keV}\right)^{-1} \tag{10}$$

The energy lost rate due to pion production is (**??**),

$$t'_{p,\gamma} = \frac{1}{2\,\gamma_p} \int_{\epsilon_0}^{\infty} d\epsilon\, \delta_\pi(\epsilon) \xi(\epsilon)\, \epsilon \int_{\epsilon/2\gamma_p}^{\infty} dx\, x^{-2}\, n(x) \tag{11}$$

where $n(x) = dn_\gamma/d\epsilon_\gamma(\epsilon_\gamma = x)$, $\sigma_\pi(\epsilon)$ is the cross section of pion production for a photon with energy ϵ in the proton rest frame, $\xi(\epsilon)$ is the average fraction of energy transferred to the pion, and $\epsilon_0 = 0.15$ is the threshold energy, $\gamma_p = \epsilon_p/m_p^2$.

The rate of energy loss, $t'_{p,\gamma}$, $f_{\pi^0,p\gamma} \approx t'_d/t'_{p,\gamma}$ (where $t'_d \sim r_d/\Gamma$ is the expansion time scale), can be calculated by following Waxman & Bahcall 1997 formalism.

$$f_{\pi^0,p\gamma} \approx \frac{(1+z)^2\, L^{obs}}{8\,\pi\,\Gamma^2\, \delta_D^2\, dt^{obs}\, E^{obs}_{\gamma,b}} \sigma_{\epsilon_{peak}}\, \xi(\epsilon_{peak})\, \frac{\Delta\epsilon_{peak}}{\epsilon_{peak}} \begin{cases} \frac{E_p^{obs}}{E_{p,b}^{obs}} & E_p^{obs} < E_{p,b}^{obs} \\ 1 & E_p^{obs} > E_{p,b}^{obs} \end{cases} \tag{12}$$

Here, $\sigma_{peak} \approx 5 \times 10^{-28}$ cm^2 and $\xi(\epsilon_{peak}) \approx 0.2$ are the values of σ and ξ at $E_\gamma \approx \epsilon_{peak}$ and $\Delta\epsilon_{peak} \approx 0.2$ GeV is the peak width.

The differential spectrum, dN_γ/dE_γ of the photon-pions produced by pγ interaction is related to the fraction of energy lost through the equation: $f_{\pi^0}(E_p)\, E_p\, dN_p/dE_p\, dE_p = E_\gamma\, dN_\gamma/dE_\gamma\, dE_\gamma$. If we take into account that π^0 typically carries 20% of the proton's energy and that each produced photon shares the same energy then, we obtain the observed gamma spectrum through the following relationship,

$$\left(E^2\, \frac{dN}{dE}\right)^{obs}_{\pi^0-p\gamma} = A_{p,\gamma} \begin{cases} \left(\frac{E_\gamma^{obs}}{E_0}\right)^{-1} \left(\frac{E_{\gamma,c}^{obs}}{E_0}\right)^{-\alpha_p+3} & E_\gamma^{obs} < E^{obs}_{\pi^0-\gamma,c} \\ \left(\frac{E_\gamma^{obs}}{E_0}\right)^{-\alpha_p+2} & E^{obs}_{\pi^0-\gamma,c} < E_\gamma^{obs} \end{cases} \tag{13}$$

where

$$A_{p,\gamma} = 2.25{\times}10^{-13}\, \frac{\delta_D^{\alpha_p}\, E_0^2\, A_p\, (11s.1)^{2-\alpha_p} e^{-\tau_{\gamma\gamma}}}{(1+z)^\alpha} \left(\frac{E^{obs}_{\gamma,c}}{\rm keV}\right)^{-1} \left(\frac{L^{obs}}{6\times 10^{43}\,{\rm erg\,s^{-1}}}\right) \left(\frac{dt^{obs}}{3.17\times 10^7 s}\right) \left(\frac{d_z}{76\,{\rm Mpc}}\right)^{-2} \tag{14}$$

and

$$E^{obs}_{\pi^0-\gamma,c} = \,{\rm GeV}\, \frac{\delta_{\rm D}^2}{(1+{\rm z})^2} \left(\frac{\rm E^{obs}_{\gamma,b}}{\rm keV}\right)^{-1} \tag{15}$$

The eq. 13 could represent the VHE photon contribution to the spectrum.

4.2 PP interaction

Hardcastle et al. 2009 argues that the number density of thermal particles within the giants lobes is $n_p \sim 10^{-4}\, cm^{-3}$. If we assume that the accelerated protons collide with this thermal particle target then, the energy lost rate due to pion production is given by (**?**),

$$t'_{pp} = (n'_p\, k_{pp}\, \sigma_{pp})^{-1} \tag{16}$$

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 $f_{\pi^0,pp} \approx t'_d/t'_{pp}$ then,

$$f_{\pi^0,pp} = R\, n'_p\, k_{pp}\, \sigma_{pp} \tag{17}$$

where R is the distance to the lobes from the AGN core.

The differential spectrum, dN_γ/dE_γ of the photon-pions produced by pp interaction is related to the fraction of energy lost through the equation: $f_{\pi^0,pp}(E_p)\, E_p\, (\frac{dN_p}{dE_p})\, dE_p = E_\gamma\, (\frac{dN_\gamma}{dE_\gamma})\, dE_\gamma$. Taking into account that photon carries 18% of the proton energy, we have that the observed pp spectrum is given by (**?**),

$$\left(E^2\, \frac{dN}{dE}\right)^{obs}_{\pi^0-pp} = A_{pp} \left(\frac{E_\gamma^{obs}}{E_0}\right)^{2-\alpha_p} \tag{18}$$

where,

$$A_{pp} = 9.97{\times}10^{-21}\, \frac{\Gamma^2\, \delta_D^2\, E_0^2\, A_p\, e^{-\tau_{\gamma\gamma}}}{(1+z)^2}\, R_{\rm kpc}\, n'_{p,{\rm cm^{-3}}} \left(\frac{dt^{obs}}{3.17\times 10^7 s}\right)^2 \left(\frac{d_z}{76\,{\rm Mpc}}\right.$$

The eq. 18 could represent the VHE photon contribution to the spectrum.

5 SUMMARY AND CONCLUSIONS

We have presented a leptonic and hadronic model to describe the broadband photon spectrum of Cen A. Our model has eight free parameters (equipartition magnetic field, equipartition electron energy, bulk Lorentz factor, spectral index, ratio of expansion time and proportionality constants). The leptonic model describes the spectrum up to a few GeV energies while the hadronic model describes the Cen A spectrum at TeV energies. Two hadronic interactions have been considered, pγ and pp interactions. In the first case, the target is considered as SSC photons with energy of $\sim$ 150 keV, while in the second case, the target protons are those in the lobes of Cen A. Only one hadronic interaction is considered at the time but in both cases, the proton spectrum is extrapolated up to ultra high energies to estimate the number of UHECR events expected at Earth. We have required a good description of the photon spectrum to obtain values for the quantities required to estimate the UHECR events.

When pγ interaction is considered, the expected number of UHECR obtained is several orders of magnitude above the observed by PAO. However, when pp interaction is considered, the expected number of UHECR is in very good agreement with PAO observations.

We have also calculated the neutrino event rate from pp interactions observed by a hypothetical Km^3 neutrino telescope in the Mediterranean sea. We have calculated the signal to noise ratio considering atmospheric and cosmic neutrino "backgrounds". We have obtained that the expected signal event rate is below the required one to disentangle the neutrino emission from Cen A from the "backgrounds".

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[h!]

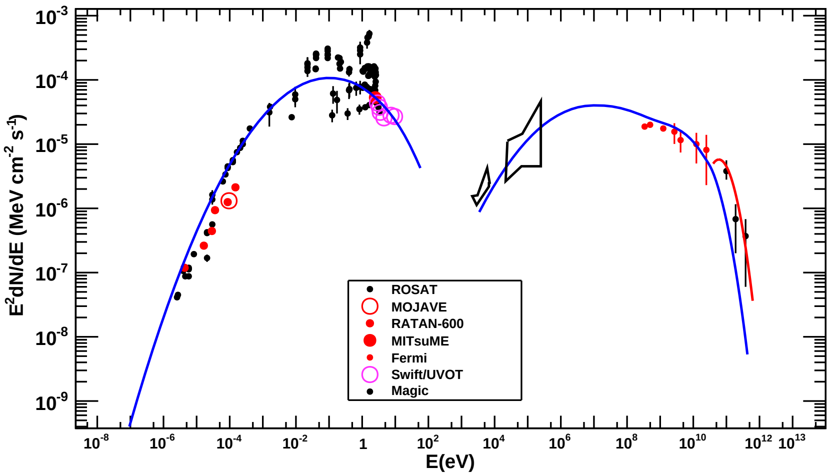

Figure 1. Fitting of observed spectral energy distribution (SED) of NGC1275. The blue line is a fit to the broadband SED using Fermi data, while the red curve is the pγ emission described in section 3.

[h!]

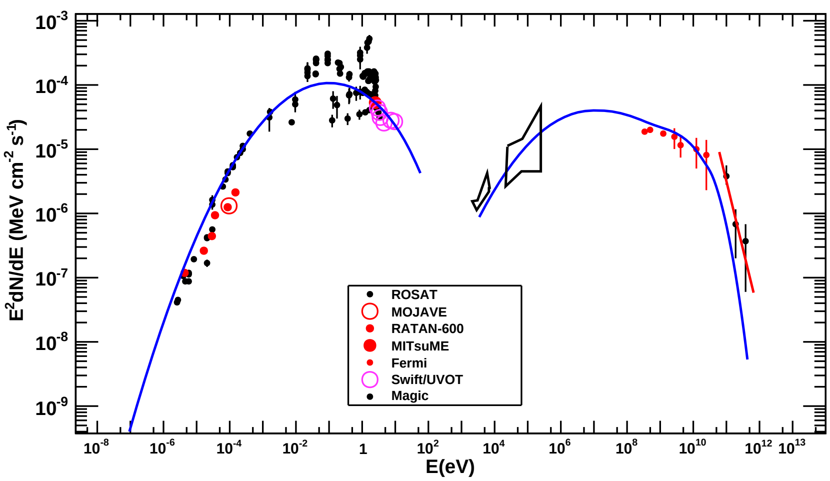

Figure 2. Fitting of observed spectral energy distribution (SED) of NGC1275. The blue line is a fit to the broadband SED using Fermi data, while the red curve is the pp emission described in section 3.

[h!]

Figure 3. App as a function of the Lobes distance for several thermal particle densities for NGC1275

APPENDIX A: CHI-SQUARE MINIMIZATION

Firstly, from pp interaction model (eq. 18), we fit the γ-ray spectrum using two parameters, the proportionality constant of pp spectrum $A_{pp,\gamma}$ (eq. **??**) and the spectral index α, as follow.

$$\left(E_\gamma^2\,\frac{dN_\gamma}{dE_\gamma}\right)^{obs}_{\pi^0} = [0]\,\left(\frac{E^{obs}_{\gamma,\pi^0}}{\rm GeV}\right)^{2-[1]}, \tag{A1}$$

After fitting we obtained the values

	Parameter	Symbol	Value
Proportionality constant ($10^{-6}\ {\rm erg/cm^2/s}$)	[0]	$A_{pp,\gamma}$	3.696 ± 1.014
Spectral index	[1]	α	4.245$\pm$ 0.8838
Chi-square/NDF		$\chi^2/{\rm NDF}$	$0.5335/1.0$

Table A1. The best set of pp interaction parameters for γ-ray spectrum of north and south lobes.

Secondly, from synchrotron emission model (eq. 7), we fit the peak at radio wavelength using four parameters, the proportionality constant of synchrotron $A_{syn,\gamma}$ (eq. 6), the spectral index α, the characteristic and cut-off photon energies $\epsilon^{obs}_{\gamma,m}$ and $\epsilon^{obs}_{\gamma,c}$ (eq. 3), respectively as follow

$$\epsilon_\gamma^2 N_\gamma(\epsilon_\gamma) = [0]\begin{cases} (\frac{\epsilon_\gamma}{[3]})^{4/3} & \epsilon^{obs}_\gamma < [3],\\ (\frac{\epsilon_\gamma}{[3]})^{-([1]-3)/2} & [3] < \epsilon^{obs}_\gamma < [2],\\ (\frac{[2]}{[3]})^{-([1]-3)/2}(\frac{\epsilon_\gamma}{[2]})^{-([1]-2)/2}, & [2] < \epsilon^{obs}_\gamma \end{cases} \tag{A2}$$

The values of the parameters obtained after fitting

	Parameter	Symbol	Value
Proportionality constant ($10^{-5}\ {\rm erg/cm^2/s}$)	[0]	$A_{syn,\gamma}$	6.163 ± 0.706
Spectral index	[1]	α	2.827 ± 0.034
Cut-off photon energy (10^{-4} eV)	[2]	$\epsilon^{obs}_{\gamma,c}$	8.507 ± 0.745
Characteristic photon energy (10^{-1} eV)	[3]	$\epsilon^{obs}_{\gamma,m}$	1.00$\pm$ 0.009
Chi-square/NDF		$\chi^2/{\rm NDF}$	$841.2/30$

Table A2. The best set of synchrotron parameters for the peak at radio wavelength of north and south lobes.