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Physics

ON THE ORIGIN OF HIGH ENERGY γ-RAYS FROM GIANT RADIO LOBES OF CENTAURUS A

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Recently the Fermi LAT collaboration reported on the detection of high energy γ-ray signal from giant lobes of the radio galaxy Centaurus A. It is shown that if the γ-rays had originated from the inverse-Compton scattering of cosmic microwave background photons for the equipartition magnetic field of 2 μG, the Fermi LAT would not detect γ-rays from the lobes of Centaurus A.

However, the detected γ-rays may be produced in hadronic interactions, namely in interactions of high energy protons with low density plasma followed with the production of pions, the neutral component decaying into 2 γ-quanta. In this article we study the hadronic origin of γ-rays, and estimate the total energy of protons assuming a power-law proton distribution with an exponential cut-off.

***Keywords*:** Centaurus A, gamma-rays, radio galaxy lobes.

Introduction. At the distance of 3.8 *Mpc*, Centaurus A (*Cen A*) is by far the nearest active radio galaxy. It is often considered to be the prototype of Fanaroff-Riley Class I [1] "low luminosity" radio galaxy, and as such it plays an important role in our understanding of the major class of active galaxies. *Cen A* is the brightest source in the Southern Hemisphere with the physical size of several hundred *kpc*. *Cen A* has a complicated structure: the core of the galaxy, outer giant lobes and inner double lobes. Outer giant lobes with physical sizes of 250 *kpc* ensue from previous jet activity and the *X*-ray observations show that the inner lobes developed as a result of current nuclear activity.

In the radio band the source is well studied up to 90 *GHz*. With the view of measuring structures in the Cosmic Microwave Background (CMB) [2] the observations of the sky as a whole have been made at frequencies around 20, 30, 40, 60 and 90 *GHz* (known as K, Ka, Q, V and W bands respectively) using the Wilkinson Microwave Anisotropy Probe (WMAP). *Cen A* has been clearly detected and spatially resolved in WMAP observations at all frequencies [3] and WMAP-derived measurements of the flux density of the source as a whole have been recently presented [4]. The spectral energy distribution (SED) of lobes and core (Fig. 1) are seen to clearly differ. The Northern lobe presumably consists of

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(at least) a flat-spectrum component and a component with spectral turnover between 5 and 20 *GHz* (the square points in Fig. 1). The spectrum of the southern giant lobe remains relatively flat up to 5 *GHz*, but clearly steepens at high frequencies (the triangles in Fig. 1). Thus, to study the variation of the radio spectrum as a function of position, one can avail himself of the above data to fit spectral ageing models to the large-scale lobes and make predictions on the expected inverse-Compton emission from the giant lobes. In Fig. 1 the flux from the core is shown by circles.

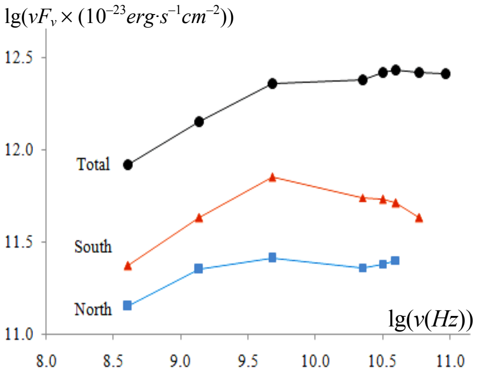

Fig. 1. Flux density×frequency for North, South lobes and total source as a function of frequency.

Here we will discuss only the origin of γ-rays from lobes of *Cen A*, since the origin of γ-rays from *Cen A* core were considered in many articles (see [5, 6]), and in particular in [5] the data of recent observation of core with Fermi LAT are compared with the observations in *TeV* energies.

Prediction of the Inverse-Compton Scattering. As is well established, the lobes of this radio galaxy are filled with magnetized plasma containing ultra-relativistic electrons which emit synchrotron radiation in the radio band. Thus, the electrons could scatter low energy photons via inverse-Compton scattering to high energies. The main target photon fields are CMB, extragalactic background light (EBL) and synchrotron radiation. As the density of CMB photons is higher than that of other fields, CMB is the predominant target photon field (EBL makes contribution only at high energies and the synchrotron photon field for *Cen A* lobes is negligible due to the huge size of the lobes).

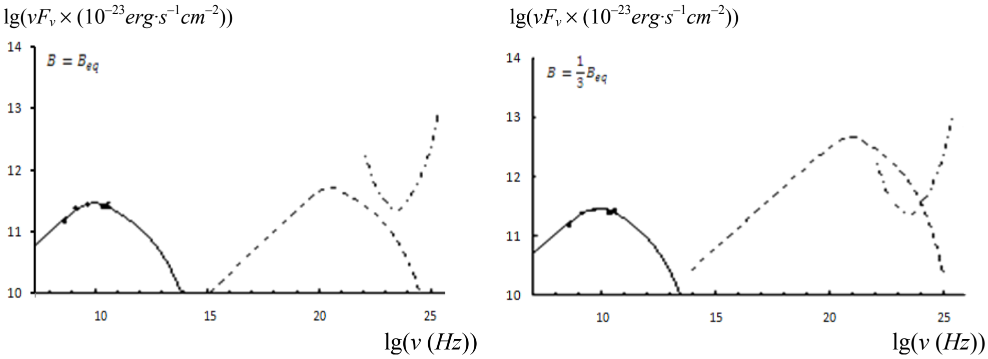

Fig. 2. SED of the *Cen A* northern lobe for magnetic field strength B=B_{eq} and B =1/3 B_{eq}. The dot dashed lines are the point-source Fermi LAT sensitivity after one year. The dashed lines show the predictions for inverse-Compton flux.

The strength of equipartition magnetic field in the lobes is estimated to be 2 μG. Thus, using this value of magnetic field and the radio observations one can find the electron energy distribution in the lobes and then make predictions for the inverse-Compton flux. In Fig. 2 (left) the predicted inverse-Compton flux is shown for the equipartition magnetic field as compared with Fermi LAT sensitivity. As the resultant flux is seen to be by the factor of 10 below the Fermi LAT sensitivity, therefore, if the magnetic field is 2 μG, the Fermi LAT would not have detected high energy γ-rays from *Cen A* lobes, if the only source of γ-rays is assumed to be the inverse-Compton scattering of CMB photons. At the same time, if the magnetic field is significantly lower than the equipartition one (something like 1/3 B_{eq}), then the upscattered CMB photons, in principle, might be detected by Fermi LAT (Fig. 2, right). The existence of thrice as less magnetic field means that the electron and magnetic field energy densities differ by a factor of 10 and even larger, if the allowance for the presence of protons within the lobes is made. The modeling of γ-rays from the lobes of *Cen A* within the leptonic scenario shows that the value of magnetic field is less than 1 μG [7].

However, when interacting with low density plasma in lobes of *Cen A* the high-energy protons can produce π^0 that would subsequently decay into γ-rays.

Fermi LAT Observation of the Lobes of *Cen A* Galaxy. During the first 10 months of observations Fermi LAT has detected high energy γ-rays from giant lobes of *Cen A*. Large fraction > 1/2 of the total > 100 *MeV* emission from *Cen A* has originated from the lobes with fluxes [8]:

Northern	$(0.77\ (+0.23/-0.19)_{stat}(\pm 0.39)_{syst})\cdot 10^{-7}\ ph\ cm^{-2}s^{-1}$;
Southern	$(1.09\ (+0.24/-0.21)_{stat}(\pm 0.32)_{syst})\cdot 10^{-7}\ ph\ cm^{-2}s^{-1}$;
the lobes are comparable with the core flux	$(1.50\ (+0.25/-0.22)_{stat}(\pm 0.37)_{syst})\cdot 10^{-7}\ ph\ cm^{-2}s^{-1}$.

As this is for the first time that γ-rays from components of radio galaxies are detected, a detailed study of their origin will be instructive for understanding the physical processes in distant radio galaxies. In the present paper the origin of γ-rays will be considered only within hadronic scenario (the leptonic origin of the γ-rays will be discussed in details in the forthcoming paper [7]).

Hadronic Origin of γ-rays. Being effectively accelerated and injected with electrons in the intergalactic medium around *Cen A* galaxy, the protons still remain energetic, because the cooling time of the protons in proton-proton interaction is:

$$t = 1/n_H ck\sigma_{pp} = 10^{15}(n_H/1\ cm^{-3})^{-1}s,$$

where n_H is the gas density, c is the speed of light, and σ_{pp} and k are the cross section and inelasticity of the proton-proton interaction. Of course, one should allow for the fact that the protons can escape from the region with diffusion, but in case of huge, 250 *kpc* size of lobes, the diffusion escape is negligible. These energetic protons can effectively interact with the ambient low density plasma, produce daughter mesons and the π^0 component that decays to 2γ.

The proton spectrum in the lobes $N_p(E_p)$ can be modelled using a power-law proton distribution with an exponential cut-off, namely:

$$N_p(E_p) = N_0(E_p/m_pc^2)^{-\alpha}\exp(-E_p/E_{\max}), \quad (1)$$

where α is the power-law index, m_p is the rest mass of proton, $E_{\max}$ is the maximum energy of protons, and N_0 constant can be expressed in terms of the total proton energy w_p:

$$w_p = \int E_p N_p(E_p)\, dE_p \,.$$

The density of gas (thermal plasma) is somewhat uncertain. Recent estimates show that its value changes within the range $n_H = (10^{-5} \div 10^{-4})\ cm^{-3}$. Using the data from soft *X*-ray emission the density to be used in calculations is estimated to be $n_H = 1.6 \cdot 10^{-4}\ cm^{-3}$ [8].

The emissivity $q_\gamma(E_\gamma)$ of γ-rays due to decay of π^0 mesons is directly defined by their emissivity $q_\pi(E_\pi)$:

$$q_\gamma(E_\gamma) = 2 \int_{E_{\min}}^{\infty} q_\pi(E_\pi) \Big/ \sqrt{E_\pi^2 - m_\pi^2 c^4}\, dE_\pi \,, \qquad (2)$$

where $E_{\min} = E_\gamma + m_\pi^2 c^4 / 4E_\pi$ and m_π is the rest mass of π^0. The emissivity $q_\pi(E_\pi)$ calculated in δ function approximation for the cross-section $\sigma_{pp}(E_p)$ reads as [9]

$$\begin{aligned} q_\pi(E_\pi) &= c n_H \int \delta\left(E_\pi - K_\pi E_{\text{kin}}\right) \sigma_{pp}\left(E_p\right) N_p\left(E_p\right) dE_p = \\ &= \frac{c n_H}{K_\pi} \sigma_{pp}\left(m_p c^2 + \frac{E_\pi}{K_\pi}\right) N_p\left(m_p c^2 + \frac{E_\pi}{K_\pi}\right), \end{aligned} \qquad (3)$$

where $\sigma_{pp}(E_p)$ is the total cross section of inelastic pp collision, K_π is the mean fraction of the kinetic energy transfer $E_{\text{kin}} = E_p - m_p c^2$ from proton to the secondary π^0-meson per collision and $N_p(E_p)$ is the energy distribution of protons. $\sigma_{pp}(E_p)$ may be approximated by [10]

$$\sigma_{pp}(E_p) = 34.3 + 1.88 \ln(E_p / 1\,TeV) + 0.25 [\ln(E_p / 1\,TeV)]^2,\ mb. \qquad (4)$$

Finally, the γ-ray spectrum is calculated using Eq. (2)–(4) on assumption that the proton spectrum is given by Eq. (1). The results are presented in Fig. 3.

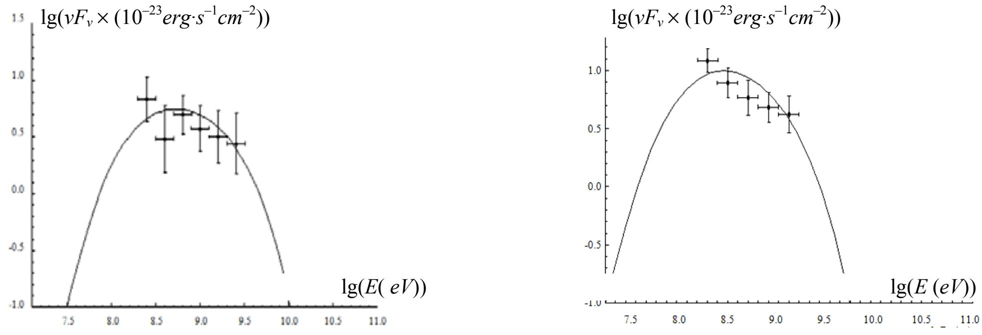

Fig. 3. SED of *Cen A* lobes under assumption that γ-rays originate in the proton-proton interaction.

The modeling parameters for the northern and southern lobes are respectively: $\alpha = 2.1$ and $E_{\max} = 18\,GeV$, $\alpha = 2.3$ and $E_{\max} = 10\,GeV$. The maximum energy in the lobes is found to be $w_p = 2 \cdot 10^{61}\, erg$. Since, the available γ-ray data do not demonstrate the cut-off feature in the spectrum, one should not consider the values of $E_{\max}$ equal 18 and 10 *GeV* as the maximum proton energy in the lobes. The results in Fig. 3 indicate that γ-rays detected by Fermi LAT from *Cen A* lobes may be naturally attributed to the proton-proton interactions.

Conclusion. The Fermi LAT observation of the *Cen A* galaxy is presented and discussed. The comparison between the radio data and Fermi LAT sensitivity show, that if the magnetic field strength is less than the estimated equipartition value of 2 μG (by the factor of 3 or higher), it is possible to detect γ-rays from *Cen A* lobe with Fermi LAT (provided that γ-rays originate from the inverse Compton scattering of CMB photons). In fact, within the leptonic scenario the fitting of SED of *Cen A* lobes from radio to γ-ray range is possible only for values of magnetic field < 1 μG [7].

However, in the article it was shown that the possibility of hadronic origin of γ-rays should not be disregarded. The formalism for the calculation of γ-ray spectrum from proton-proton interactions was presented and assuming the power law spectrum with exponential cut-off. The total energy of hadrons in the lobes was estimated to be

$$w_p \leq 2\cdot 10^{61}\left(\frac{n_H}{1.6\cdot 10^{-4}}\right)^{-1} erg\,,$$

that should be considered as an upper limit of the hadron content in the lobes due to uncertainties in measurement of the thermal plasma density. Based on the estimate of total energy of electrons that proved equal to $1.5\cdot 10^{58}$ *erg* [8], the proton-to- -electron ratio in *Cen A* lobes was $w_p / w_e \approx 1000$ (for comparison in our Galaxy $w_p / w_e \approx 100$).

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