АСТРОФИЗИКА

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HIGH ENERGY γ-RADIATION FROM THE CORE OF RADIO GALAXY CENTAURUS A

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The results of analysis of approximately 3 year gamma-ray observations (August 2008-July 2011) of the radio galaxy Centaurus A with the Fermi Large Area Telescope (Fermi LAT) are presented. By modeling the surrounding (background) sources including the giant lobes of Centaurus A, and using the standard binned likelihood analysis method, the energy spectrum of the core is derived. In the energy range below several GeV it is described by a single power-law with photon index $\Gamma = 2.73 \pm 0.06$ in agreement with the report of the Fermi LAT collaboration based on the first 10 months observations of the source. However, at higher energies the new data show significant excess above the extrapolation of the energy spectrum from low energies. The total flux between 200 MeV to 50 GeV is estimated $(1.63 \pm 0.14) \times 10^{-7}$ ph cm^{-2} s^{-1}. The comparison of the corresponding Spectral Energy Distribution (SED) at GeV energies with the SED in the TeV energy band reported by the H.E.S.S. collaboration shows that we deal with two or perhaps even three components of gamma-radiation originating from different regions located within the central 10 kpc of Centaurus A.

Key words: *Centaurus A:gamma-rays:radio galaxy*

1. *Introduction*. At a distance of 3.8 Mpc the peculiar elliptical radio galaxy NGC 5128 (Centaurus A) is the nearest active radio galaxy and one of the best studied extragalactic objects. It is often treated as a prototype Fanaroff-Riley Class I [1] low-luminosity radio galaxy. With the size of ≈ 600 kpc, it has an interesting structure: giant radio lobes with an angular extent of 10° oriented primarily in the north-south direction, a relativistic jet extending to kpc scales, inner double lobes and a compact core. The observations of hot thermal X-ray emission show that the inner lobes are a result of the current nuclear activity. It is generally believed that the energy is extracted from the central black hole of mass $\approx 10^8 M_\odot$.

Recently the Fermi LAT collaboration reported the detection of high energy gamma-rays from both the north and south giant radio lobes [2]. It has been suggested that this radiation is the result of inverse Compton scattering of cosmic microwave background photons and the extragalactic background light photons by *in situ* accelerated electrons [2].

The central inner part (the core) of the radio galaxy was previously detected by EGRET (Energetic Gamma-Ray Experiment Telescope) with marginal statistical significance of about 3σ and energies up to several hundred MeV

[3]. The core of Centaurus A was a target of long-term observations by the H.E.S.S. (High Energy Stereoscopic System) imaging atmospheric Cherenkov telescope array. These observations resulted in detection of γ -rays were detected up to energies of 5 TeV [4]. According to the HESS data, the power-law photon index of the source is $\Gamma = 2.73 \pm 0.45_{stat} \pm 0.2_{syst}$, and integral flux above 250 GeV is $\Phi \quad (E > 250\,\mathrm{GeV}) = (1.56 \pm 0.67_{stat}) \times 10^{-12}$ ph cm^{-2} s^{-1} [4].

The detection of Centaurus A by EGRET was confirmed by Fermi LAT telescope, earlier with the three month of data [5] and later on with the 10 month of all-sky survey data. The Fermi LAT data show that the power-law photon index for the energies between 200 MeV and 30 GeV is $\Gamma = 2.67 \pm 10_{stat} \pm 0.08_{syst}$ and the flux extrapolated down to >100 MeV is $(1.50 \pm 0.25_{stat} \pm 0.37_{syst}) \times 10^{-7}$ ph cm^{-2} s^{-1} [6].

In this paper we analyze the available Fermi LAT data accumulated over the last ~3 years (from August 4th 2008 to July 7th 2011), with the objective to study of spectral properties of the gamma-ray emission from the core of Centaurus A, as well as to explore the possible time variability of the gamma-ray flux.

2. *Data analysis*. The data used for present studies of the core of radio galaxy Centaurus A is based on approximately 3 years of continuous sky survey over the period from August 4th 2008 to July 7th 2011 (corresponding to Mission Elapsed Times (MET) 239557420 - 331755684). For the analysis photons within a rectangular Region of Interest (ROI) of size 14° x 14° centered on the position of Right Ascension (RA) and Declination (Dec) (RA, Dec) = (201.47,-42.97) [7]. The energy band covers from 200 MeV to 50 GeV. For the lower energy bound one sets the limit of 200 MeV since at lower energies the effective area of Fermi LAT is rapidly reduced, and the angular resolution becomes too large. On the other hand, the limit of photon statistics determines the upper bound of 50 GeV. Also, a zenith angle cut of <105° was introduced in order to exclude the albedo atmospheric γ rays that can be a significant source of background.

For the data analysis, the Fermi LAT Science Tools version v9r23p1 was used with the Instrument Response Function (IRF) P6_V11_ DIFFUSE. The galactic and extragalactic components as well as the residual instrumental backgrounds are modeled using the Fermi LAT standard diffuse background models gll_iem_v02_P6_V11_DIFFUSE.fit and isotropic_iem_v02_P6_V11_DIFFUSE.txt[1]. For both models, the overall normalization is kept as a free parameter.

Within 14° x 14° rectangular ROI centered on Centaurus A there are 11 point sources from 1FGL catalog (see Table 1) not associated with Centaurus A. Therefore we include them in our source model as background. To describe the spatial extent of the lobes the Wilkinson Microwave Anisotropy Probe

[1] *http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html*

(WMAP)-k template (see NASA's SkyView[2]) is used. The template is divided in two parts in order to have separately modeling possibilities for the north and south lobes, and to exclude the emission of the core of Centaurus A we set all pixels values to zero for those pixels which are within a radius of 1° around the core. The spectra of Centaurus A and 11 point sources were modeled by power-law and the values of photon indexes as well as the overall normalization are considered as free parameters.

Table 1

THE RA (α_{J2000}) and Dec (δ_{J2000}) OF 11 POINT SOURCES WITHIN ROI THAT HAVE BEEN INCLUDED IN THE MODELING OF BACKGROUND OF THE REGION AROUND THE CENTAURUS A

Name	α_{J2000}	δ_{J2000}
1FGL J1300.9-3745	$13^h00^m54^s$	-37°45'36"
1FGL J1304.0-4622	13 04 05	-46 22 06
1FGL J1304.3-4352	13 04 21	-43 52 07
1FGL J1305.4-4928	13 05 28	-49 28 15
1FGL J1307.0-4030	13 07 06	-40 30 37
1FGL J1307.6-4259	13 07 38	-42 59 58
1FGL J1320.1-4007	13 20 10	-40 07 36
1FGL J1328.2-4729	13 28 12	-47 29 56
1FGL J1334.2-4448	13 34 15	-44 48 48
1FGL J1347.8-3751	13 47 52	-37 51 18
1FGL J1400.1-3743	14 00 08	-37 43 04

At the data preparation we use gtselect tool in order to make cuts based on events data file such as time, energy, position, zenith angle, instrument coordinates and event class, and gtmktime tool to make cuts based on the spacecraft file and updates the good time interval extension.

To make a three-dimensional counts map (which is required for binned likelihood analysis) with an energy axis we use gtbin tool with the energy binned logarithmically in 20 bins in the interval from 200 MeV to 50 GeV.

3. *Spatial and Spectral Analysis.* After the data preparation as described in the previous section with the gtlike tool we performed the binned likelihood analysis. For the Centaurus A core it gives TS = 990 which corresponds to the detection significance $\approx 31\sigma$. The likelihood ratio Test Statistic (TS) is defined as $TS = 2(\log L_{source} - \log L_{nosource})$, where L represents the likelihood of the data given the model with or without a source present at a given position on the sky.

Fig.1 shows the Spectral Energy Distribution (SED) for the core of Centaurus

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[2] *http://skyview.gsfc.nasa.gov/*

A with the best power-law fit in whole energy range. The normalization of galactic and isotropic models become 1.03 ± 0.02 is 1.33 ± 0.05. The power-law fit gives for the photon index $\Gamma = 2.73 \pm 0.06$ within the 200 MeV and 50 GeV energy interval and the total flux $(1.63 \pm 0.14) \times 10^{-7}$ ph cm^{-2} s^{-1} above ~200 MeV. In the EGRET catalog [3] similar numbers, namely the photon index $\Gamma = 2.58 \pm 0.26$ and integral flux $(1.36 \pm 0.25) \times 10^{-7}$ ph cm^{-2} s^{-1} with TS = 9 have been reported.

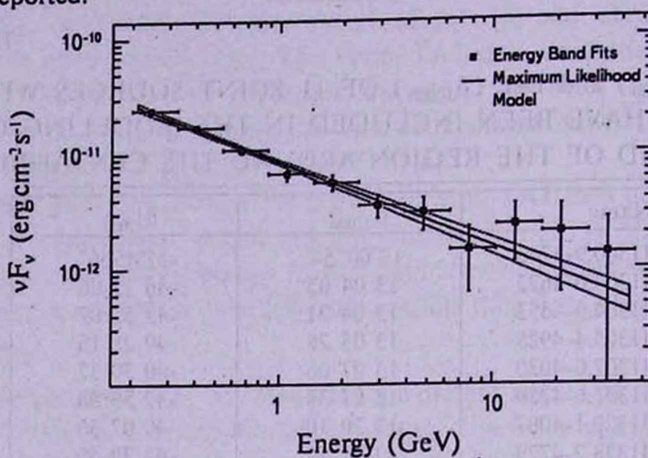

Fig.1. Spectral energy distribution of the core of Centaurus A with the best power-law fit in the energy range 200 MeV-50 GeV.

4. *Time Variability*. For the investigation of variations of the flux and the photon index from the core of Centaurus A the time period from August 4th 2008 to July 7th 2011 has been analyzed. To quantify the variability we generate the light curve of Fermi LAT data in the 30 day bins using the binned likelihood analysis with gtlike tool. The underlying background diffuse emission is not expected to have variability therefore we fixed the normalization value obtained for overall energy range (200 MeV ÷ 50 GeV) for the whole observation time. We also fixed the power-law photon indexes for all background sources used in our source model (north and south lobes +11 background sources) and we set as free parameters the power-law normalization of all sources and index of core too. In Fig.2 the plot of variation of flux (upper panel) and photon index of the core (lower panel) are presented as a function of time in Modified Julian Days (MJD). We use standard χ^2 test, by the definition of [8], resulting to $\chi^2 = 19(\chi^2/\mathrm{DOF} = 0.56)$.

The results presented in Fig.2 show that the time behavior of the core of Centaurus A. Although the gamma-ray light curve shows possible variation of the gamma-ray flux on scales of 1 month, within a factor of two or so, unfortunately the poor statistics does not allow a definite conclusion in this regard. It should be noted that the observations of the core of Centaurus A with the H.E.S.S. telescope array also did not reveal significant variability at very high energies [4]. For comparison, the GeV and TeV gamma-ray fluxes of blazars show strong (up to a factor of 10) variability both on short (mins) and long (months) timescales.

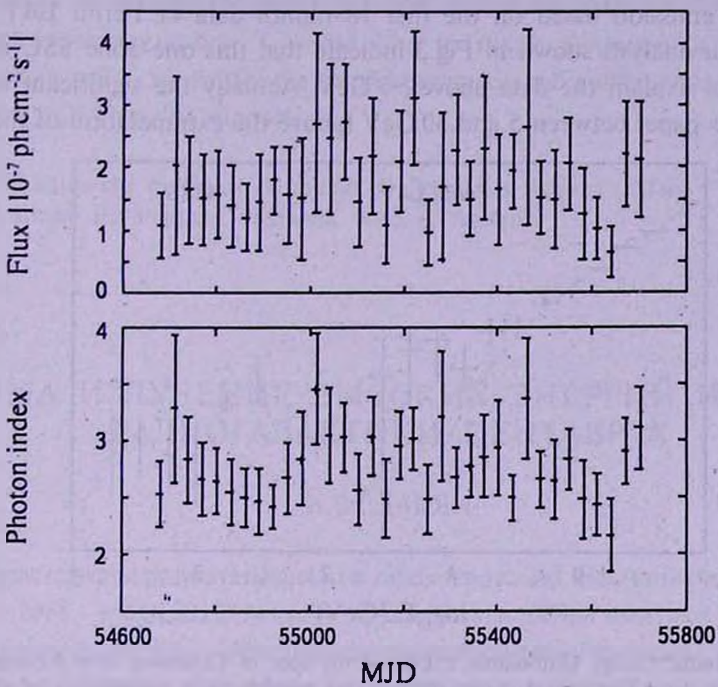

Fig.2. The temporal variation of γ -ray flux and the photon index for the period from August 4th 2008 to July 7th 2011.The size of bins is 30 day, and background diffuse emission (both galactic and extragalactic) is fixed to the best fit parameters obtained for the overall time fit.

5. *Discussion and Spectral Energy Distribution.* In Fig.3 we show the obtained Spectral Energy Distribution (SED) for the core of Centaurus A and comparison with the H.E.S.S. data. The angular resolutions of both the H.E.S.S. array of about 0°.1 (or worse) and the Fermi LAT 0°.1-1° (depending on energy) correspond to the linear size of the gamma-ray emitting region(s) of about 5 kpc or larger. The 5 kpc region contains several prominent components including the sub-pc and kpc scale jets, inner lobes, the compact core with suspected $\approx 10^8 M_{\odot}$ black hole inside, the elliptical galaxy itself, etc. All these regions are potential gamma-ray emitters. The limited angular resolutions of gamma-ray detectors do not allow to localize the regions of gamma-ray production. The lack of statistically significant variations also do not provide an information whether the gamma-rays are produced in compact objects (i.e. in sub-parsec jets or in the vicinity of central the black hole) or they originate from extended regions (e.g. the kpc jets or inner lobes). This unfortunately introduces significant uncertainties regarding the origin of gamma-rays. On the

other hand the results of this paper indicate that most likely we deal with one or perhaps more gamma-ray sources contributing to the emission in different energy bands. In this regard, it is interesting to note that in ref. [6] a simple one-zone synchrotron-self-Compton model has been proposed to explain the gamma-ray emission based on the first 10 month data of Fermi LAT. The results of our analysis shown in Fig.3 indicate that this one-zone SSC model alone cannot explain the data above ~5 GeV. Actually the significant excess found in this paper between 5 and 30 GeV (above the extrapolation of the flux

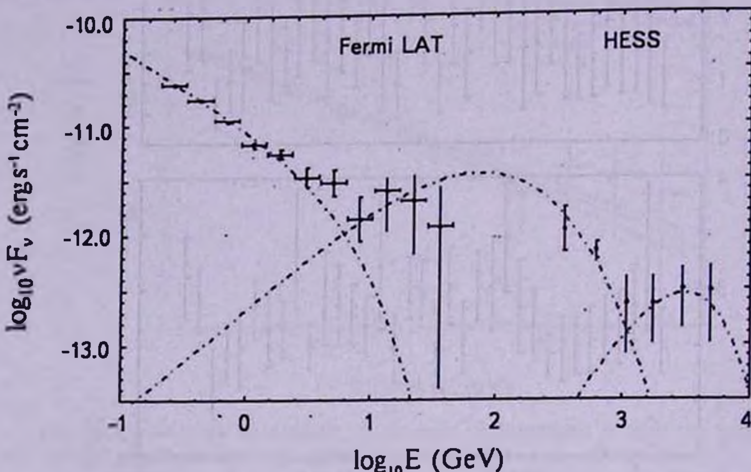

Fig.3. Spectral Energy Distribution (SED) of the core of Centaurus A and comparison with the HESS data. The dashed curves illustrate the possible three components of gamma-radiation in the core.

from lower energies) has more general implication. Most likely this is a new component which perhaps can account also for the gamma-ray fluxes below 1 TeV reported by the H.E.S.S. collaboration [4] (first 3 points in Fig.3). Meanwhile the fluxes of multi-TeV electrons detected by H.E.S.S. [4] seem to be belong another component of radiation. The interpretation of the complex structure of gamma-ray spectrum of the core as a result of superposition of different radiation components seems quite natural given the presence of several potential sites for gamma-ray production within the central 10 kpc region of the peculiar galaxy.

Hopefully more observation data from Fermi LAT and H.E.S.S. should be able to provide deeper understanding of γ -rays emission production sites and particle acceleration and radiation mechanisms in the core of Centaurus A.

6. *Summary*. The gamma-ray Fermi LAT observations of the core of radio galaxy Centaurus A accumulated over three years (from August 4th 2008 to July 7th 2011) have been analyzed.

For the energy range from 200 MeV to 50 GeV the total flux of the core of Centaurus A is estimated $(1.63 \pm 0.14) \times 10^{-7}$ ph cm^{-2} s^{-1}. Below several GeV the energy spectrum can be represented by a single power-law with photon index $\Gamma = 2.73 \pm 0.06$, however above 5 GeV the spectrum shows significant excess which can be a result of a new additional component of radiation. No statistically significant variability has been found on scales of months.

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ГАММА ИЗЛУЧЕНИЕ ВЫСОКИХ ЭНЕРГИЙ ИЗ ЯДРА РАДИОГАЛАКТИКИ ЦЕНТАВР А

Н.В.СААКЯН

Представлены результаты анализа приблизительно трехлетних наблюдений (август 2008 - июль 2011) гамма-излучения ядра радиогалактики Центавр А с помощью Ферми LAT. Моделированием окружающих (фоновых) источников, включая гигантские радиолепестки Центавр А и используя стандартный метод вероятного анализа, выведен энергетический спектр ядра. В диапазоне энергий ниже нескольких ГеВ он описывается единственным степенным законом с индексом $\Gamma = 2.73 \pm 0.06$ в соответствии с докладом Ферми LAT, сделанной на основе наблюдений первых 10-ти месяцев. Однако на более высоких энергиях новые данные показывают значительный избыток по сравнению с экстраполяцией спектра низких энергий. Оценка полного потока между 200 МэВ и 50 ГэВ получается $(1.63 \pm 0.14) \times 10^{-7}$ фотон см$^{-2}$ с$^{-1}$. Сравнение соответствующего Распределения Спектральной Энергии (РСЭ) в области ГэВ с РСЭ в ТэВ, которое было представлено сотрудничеством H.E.S.S., показывает, что мы имеем дело с двумя или, возможно, тремя компонентами гамма-излучения, которые возникают в различных областях, находящихся в центральной сердцевине Центавр А размерами 10 кпк.

Ключевые слова: *Центавр А:гамма-излучение:радиогалактика*

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