Detection of Sub-TeV gamma-rays from the Galactic Center with the CANGAROO-II telescope

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Abstract.
The Galactic Center has been observed with the CANGAROO–II imaging atmospheric Cherenkov telescope in 2001 and 2002. We detected a statistically significant excess at energies greater than 250GeV. This is the first detection of sub-TeV gamma rays from the Galactic Center region. The signal direction is consistent with the Galactic Center, which includes the massive black hole Sgr A* and supernova remnant Sgr A East. The resultant flux is 1 order of magnitude lower than that of the Crab Nebula at 1 TeV. The differential flux has a steep spectrum and the power law index is observed to be -4.6 ± 0.5, although it could flatten to -3.4 if the uncertainty in energy determination is included. Here, the analysis for reduction of night sky background effects and the radiation mechanism of sub-TeV gamma rays are reported. The most probable radiation mechanism is π^0 decays. The maximum energy of the inferred cosmic rays is 1-3 TeV and the total cosmic-ray luminosity corresponds to $1 \sim 10$ supernova remnants. We also obtain an upper limit on the cold dark matter density in the galactic halo.

INTRODUCTION

Observations of the Galactic Center are being actively pursued from radio to gamma-ray wavelengths. They indicate that the central region contains (among other components) a super massive black hole, diffuse hot gas and a supernova remnant. Emission of high energy gamma-rays from the Galactic Center region still remains to be fully exploited compared with observations at lower energies. The EGRET instrument on the Compton Gamma-Ray Observatory observed the Galactic Center region. Mayer-Hasselwander et al. reported strong emission in the energy region from 100 MeV to 10 GeV [16]. However, it is not yet clear whether it is a point source or a diffuse source. Time variability is reported, although its amplitude is not large [19]. Various theories have been suggested for the origin of the high energy emission: the accretion disk around the massive black hole [14][15], the radio arc [20] or supernova remnants [11][17]. If the high energy radiation continues up to the sub-TeV gamma-ray region, or has a cut-off in the spectrum in the TeV gamma-ray region, observations with Imaging Air Cherenkov Telescopes (IACTs) will provide important information to help determine the high energy radiation mechanism. From point of view of particle physics, annihilation of putative dark matter neutralinos might be the origin of the gamma-rays from the Galactic Center. A substantial density enhancement near the center and neutralino annihilation rate larger than that predicted previously give IACTs a chance of detecting a gamma-ray signal in the 100 GeV–10 TeV region [3].

From the northern hemisphere, the Whipple group and the HEGRA group reported upper limits on the gamma-ray fluxes at 2 TeV [5] and 4.5 TeV [1], respectively. Observations from the southern hemisphere have advantages owing to the higher elevations of the Galactic Center than are possible from the northern hemisphere, i.e., a lower energy threshold and longer observing period each day.

The CANGAROO-II telescope is a 10m IACT near Woomera, South Australia ($31^\circ 06' S, 136^\circ 47' E$,160m asl). The imaging camera has 552 pixels, each of which subtends an angle of 0.115°, with a total field-of-view of 2.8 degrees. We observed the Galactic Center in July 2001 and July–August 2002 with the CANGAROO-II telescope. We have reported the detection of Very High Energy (VHE) gamma-rays from the Galactic Center [24][25]. Here, we report the analysis method, particularly for treatment of the Night Sky Background, and discuss three possible mechanisms for the production of TeV gamma rays: (i) π^0 decays, (ii) inverse Compton emission in Sgr A* and Sgr A East (or SNRs), assuming the radio data is due to the synchrotron radiation, and (iii) annihilation gamma rays from Cold Dark Matter (CDM), allowing us to constrain parameters for CDM.

ANALYSIS

Randomly triggered pixels by the Night Sky Background (NSB) are discriminated from shower events in the off-line analysis. For every event, information on the relative arrival time with Time-to-Digital Converters (TDCs) and the number of photoelectrons with Analog-to-Digital Converters (ADCs) is recorded for each Photo-Multiplier Tube (PMT) pixel. The PMTs are calibrated with a blue LED flasher before each observation. Flat fielding and time-walk corrections are carried out using this data.

The noise reduction and the selection of clustered images, which enhance Cherenkov photon images of showers, were carried out as pre-selection processes. Fig.1 (left) shows the arrival time distribution for all pixels for events. We can distinguish the NSB from the shower events since the shower events have a peak in the TDC distribution. The shower region is defined as 240-340 TDC counts (100ns) and the NSB region is the excluded region. Fig.1 (right) shows ADC distributions with the shower region and with the NSB region in the TDC distributions. The ADC distribution in the shower region has a peak of 250 ADC counts ($\sim$ 2.8 photoelectrons).

The procedures of pre-selection processes are (1) pixels must have pulse heights greater than 300 ADC counts ($\sim$ 3.3 photoelectrons), (2) pixels must be triggered within 40 ns of the timing center of the event, and (3) the image includes only pixels in clusters of at least five hit pixels. Accidental events due to the NSB are reduced by 99.8 % after these procedures.

After the pre-selection, we rejected the data in which the shower rate was less than 2 Hz in order to exclude data affected by cloud or dew on the mirrors. The remaining observation time was 66 hours for the ON-source data and 57 hours for the OFF-source data, respectively.

Images from gamma-rays have compact, elliptical shapes with the major axes oriented

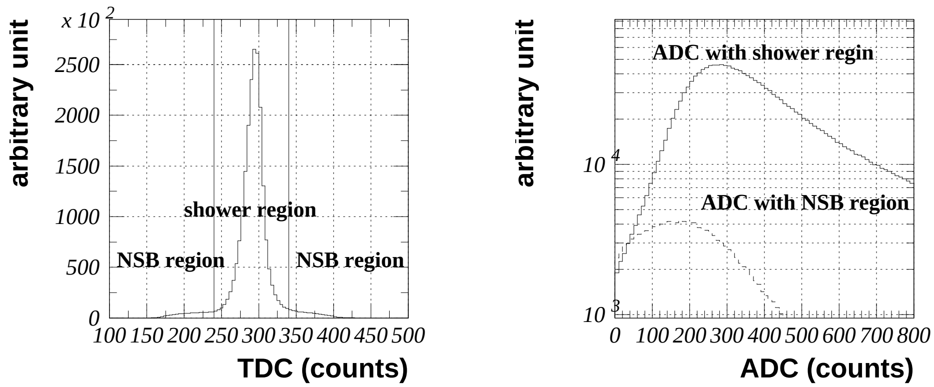

FIGURE 1. (left) Arrival time distribution for all pixels for events. Night Sky Background (NSB) is discriminated from the shower events. The shower region is defined as 240-340 TDC counts (100ns) and the NSB region is the other region. (right) ADC distributions with the shower region (solid) and with the NSB region (dashed) in the TDC distributions. The pixels which have pulse heights greater than 300 ADC counts (~ 3.3 photoelectrons) are cut and the pixels triggered within 40ns of the timing center of the event are selected.

toward the location of the source in the focal plane. In contrast, Cherenkov images from hadronic cosmic-ray showers are much more irregular and randomly oriented. The difference between images produced in gamma-ray and cosmic-ray showers can be quantified by Monte Carlo simulations (for gamma-rays) and OFF-source data (for cosmic rays). Our imaging analysis was based on the method of likelihood analysis [6] using image parameters [9]. This analysis gives a signal-to-noise (S/N) ratio and an acceptance better than those by the standard method [10]. The image parameters strongly depend on the energy of initiating shower. Therefore, a two-dimensional (2D) likelihood analysis [23] was used to take this effect into account.

RESULTS

The alpha (orientation angle) distributions after imaging cuts show a excess around $\alpha \sim 0^\circ$ (See Fig. 1 in [25]), indicating a gamma-ray signal with an energy threshold of about 250 GeV. The signal direction is consistent with the Galactic Center, which includes the massive black hole Sgr A* and supernova remnant Sgr A East. The observed profile is consistent with a point-like source. Also the EGRET source 3EG J1746$-$2851 is located within the 1 σ statistical error radius. Our data suggest that the GeV source is identical to this TeV source. The resultant flux was 1 order of magnitude lower than that of the Crab Nebula at 1 TeV. The differential flux has a steep spectrum with an observed power law index of -4.6 ± 0.5. The uncertainty of ± 0.5 is statistical only, and does not include the uncertainty in energy determination. If an uncertainty of 20% is included in each energy bin, the resulting spectrum could flatten (at the 1 sigma level) to -3.4

RADIATION MECHANISM

Proton-proton Here we evaluated the cosmic-ray flux under the assumption that both the EGRET [8] [16] and TeV radiation are due to high-energy proton interactions with the interstellar matter. The energy spectrum of protons accelerated by Supernova Remnant (SNR) shocks is expected to be a power law with some energy cut off, i.e., maximum acceleration energy (E_{max}), which is usually approximated by an exponential function. We adopted an energy spectrum of $\propto E^{-\gamma} e^{-E/E_{max}}$ (γ is 2.0–2.4) from the EGRET data and also conventional diffusive shock acceleration theories [4]. Fig. 2 shows the Spectral Energy Distribution (SED) of the GC region. EGRET data is plotted from [16] and the 3rd EGRET catalog (3EG) [8]. The number density of the ambient gas (n) was taken to be $\sim 10^3$ cm^{-3} [13]. The various lines shown in Fig. 2 are for differing values of γ and E_{max}. The GeV spectrum given in 3EG [8] differs from that of the dedicated analysis of [16], however, in both cases the EGRET and CANGAROO-II data can be relatively smoothly connected, with a cutoff energy of 1–3 TeV. The spectra for $\gamma = 2.4$ yield slightly worse fits to the data at the lowest energies. The inferred total cosmic-ray energy greater than 1 GeV corresponds to $\leq 10\%$ of a typical supernova energy, a quite plausible conversion efficiency. The details, however, are dependent on the EGRET flux. In the case of a lower gas density (n), the cosmic ray energy exceeds that of a single supernova (1–10 SNRs). Also we should consider the possibility of other sources in the GC region, such as Sgr A* itself, contributing to the gamma-ray flux.

Electron origin Here we use the model described in [26]. The calculation uses a simple δ function centered on the characteristic frequency instead of the full function describing synchrotron emission ([22] and references therein) and black body radiation (δ-function approximation). We also assumed that the radiation of sub-TeV gamma rays is due to inverse Compton scattering of infrared photons. In this case we need a number of parameters to fit the spectrum (magnetic field, maximum energy of cosmic-ray electrons, and the ratio of emission volume of inverse Compton emission for synchrotron radiation) in either Sgr A* or Sgr A East. Some exotic combinations of parameters marginally fit the multi-wavelength spectrum. However, these models are not simple.

Dark matter The annihilation gamma rays from Cold Dark Matter (CDM) is a fascinating scenario for interpreting the VHE gamma-rays from the Galactic Center. We can constrain the parameters for CDM. We follow the method described in [7]. The annihilation to quark - anti quark pair in the volume of the Galactic Center region should be detected at a rate of $F = \langle \sigma v \rangle B_{q\bar{q}} n^2 [V/(4\pi d^2)]$, where σ is the annihilation cross section, v the relative velocity of CDMs, $B_{q\bar{q}}$ the branching fraction of $\chi\chi \rightarrow q\bar{q}$, n the number density of CDM, V the size of the Galactic Center region, and d the distance from Earth, respectively.

We consider the energy spectrum of gamma rays. If the annihilation gamma rays should have the exponential function in TeV region, then its contribution to the GeV region is negligibly small in the SED. The well-known physical process to have a certain energy scale is a fragmentation function ($\frac{1}{\sigma_h} \cdot \frac{d\sigma}{dx}$, where x is a Feynman x) for such an inclusive particle spectrum as $e^+e^- \rightarrow q\bar{q} \rightarrow \gamma X$. It is typically fitted

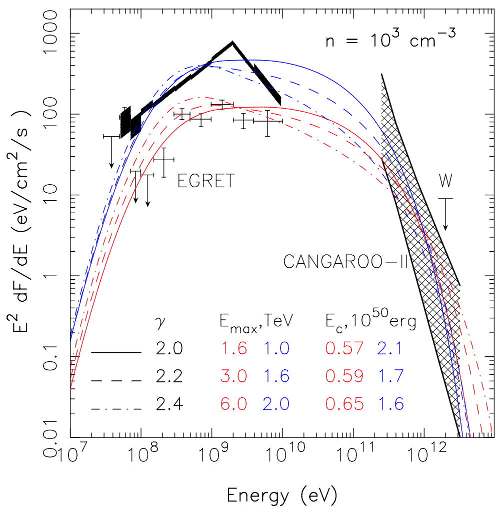

FIGURE 2. Spectral Energy Distribution of the GC region. The cross-hatched area is the 1 σ allowed region for the TeV observations [25]. The arrow (W) is the Whipple 2 σ upper limit at 2 TeV [5]. The two analyses of the EGRET data are shown by the black hatched region [16] and the crosses [8]. The lines are estimations for π^0 gamma-rays, the details of which are given in the body of the figure and in the text.

with the sum of the exponential functions. The resultant upper limit of CDM density in the Galactic Center is $\rho_{47pc} \sim 5300 GeV/cm^3$ (47pc is defined by point spread functionof CANGAROO-II).

Here we estimate the upper limit for local CDM density assuming the cusp structure of the Galactic Center. We use generalized Navaro-Frenk-White universal density profile of CDM [18]. The density profile ($\rho_{CDM}(r)$) is denoted as $\rho_{CDM}(r) \propto \frac{\rho_0}{(\frac{r}{r_s})^{\alpha}(1+\frac{r}{r_s})^{3-\alpha}}$ where r is the distance from the Galactic Center, r_s is the core radius, α is the parameter from 1.0 to 1.5, which is obtained by the results of N-body simulations of hierarchical clustering in CDM cosmology. Here we take 1.3 as α. This profile indicate that the CDM density (ρ_{47pc}) is 860 times higher than the local CDM density ($\rho_{8.5kpc}$) around the Earth. Therefore the upper limit of local CDM density is $\rho_{8.5kpc} \sim 6 GeV/cm^3$.

This is still higher than the expected local density of the CDM (∼0.3 GeV/cm^3).

DISCUSSION

Our results are consistent with the energy spectrum detected by EGRET under assumption when the energy spectrum is a power law + exponential cut off such as $E^{-\gamma} exp(-\frac{E}{E_{MAX}})$, suggesting the origin of TeV gamma rays are π^0 decay products.

The gamma-ray detection is comfirmed by VERITAS [12] and H.E.S.S. [2][21], however the spectra all differ. Inadequate treatment of NSB effects can produce an apparently steep spectrum, however, accidental hit by NSB photons are almost rejected in preselection with arrival time, number of photoelectrons, and clustering cuts. Stereoscopic observation systems such as H.E.S.S. and CANGAROO-III have better energy resolution and angular resolution than a single telescope. Studies of the radiation mechanism will be further developed in future stereoscopic observations with CANGAROO-III.

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