The Astrophysical Journal, 596:216–219, 2003 October 10

CONSTRAINTS ON COLD DARK MATTER IN THE GAMMA-RAY HALO OF NGC 253

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Received 2003 June 3; accepted 2003 June 25

ABSTRACT

A gamma-ray halo in the nearby starburst galaxy NGC 253 was found by the CANGAROO-II Imaging Atmospheric Cerenkov Telescope. By fitting the energy spectrum with expected curves from cold dark matter (CDM) annihilations, we constrain the CDM annihilation rate in the halo of NGC 253. Upper limits for the CDM density were obtained in the wide mass range between 0.5 and 50 TeV. Although these limits are higher than the expected values, they are complementary to the other experimental techniques, especially considering the extended energy coverage. We also investigate the next astronomical targets to improve these limits.

Subject headings: dark matter — galaxies: individual (NGC 253) — gamma rays: theory

1. INTRODUCTION

Recently, the gamma-ray halo in the nearby starburst galaxy NGC 253 was detected by the CANGAROO-II Imaging Atmospheric Cerenkov Telescope (IACT) (Itoh et al. 2002, 2003b). Although it seems to be successfully interpreted as a high-energy cosmic-ray halo (Itoh et al. 2003a), we assumed that this radiation is due to cold dark matter (CDM) annihilation and obtained the upper limits of the CDM density in a wide mass range around a few TeV.

The motivation of this study is the morphology obtained in a TeV gamma-ray observation (Itoh et al. 2002, 2003b), which marginally differs from a disk shape. Considering the existence of this halo (Ostriker & Peebles 1973), it would be worth obtaining the constraint of CDM by using the observed TeV emissions.

In this paper we assume two processes: inclusive gamma-ray production via the annihilation of weakly interacting massive particles to quark-antiquark pairs (Rudaz & Stecker 1988) and monochromatic gamma ray production from annihilation to the two-gamma state (Bergström & Snellman 1988). The former final states produced many more gamma rays and gave better upper limits than the latter method. The final-state gamma rays should show an exponential energy spectrum that differs from the usually known cosmic-ray spectrum, i.e., a power law.

2. PROPERTY OF NGC 253

The nearby starburst galaxy NGC 253 is located inside the Sculptor group, and can be clearly seen from the southern hemisphere. The distance was estimated to be 2.5 Mpc (de Vaucouleurs 1978). It was classified as SABc (Hubble classification), and is one of the closest examples of an object similar to our Galaxy. It is edge-on, i.e., suitable for distinguishing its halo from the disk. The optical (Beck, Hutschenreiter, & Wielebinscki 1982) and radio halos (Hummel, Smith, & van der Hulst 1984; Carilli et al. 1992) were previously observed in this galaxy, the sizes of which (~10 kpc) approximately agree with a TeV energy gamma-ray observation (13–26 kpc; Itoh et al. 2003b).

H I studies on the Sculptor group galaxies were carried out by Puche & Carignan (1991). Calculating the rotation curves, they concluded that many galaxies in this group have massive halos. In particular, that of NGC 253 was estimated to have a density of 0.015 $M_{\odot}$ pc^{-3} and a radius of 26.9 kpc, which is also within the size estimation of the TeV energy gamma-ray halo (Itoh et al. 2003b).

3. ENERGY SPECTRUM AND MASS OF CDM

The spectral energy distribution (SED) of GeV to TeV gamma rays is plotted in Figure 1. The points with error bars were obtained by CANGAROO-II (Table 6 of Itoh et al. 2003b). The arrows are upper limits obtained by EGRET (Streekmar et al. 1994; Blom, Paglione, & Carraminana 1999). According to a theoretical estimation motivated by the cosmic-ray radiation (Itoh et al. 2003a), neither a simple power-law spectrum ($\propto E^{-\gamma}$) of cosmic rays (curve A) nor one with a high-energy cutoff ($\propto E^{-2}e^{E/E_{\max}}$; curve B, due to $\pi^0 \to \gamma\gamma$ decays or bremsstrahlung) could simultaneously explain both data. These curves can be well fitted to the TeV data; however, they are inconsistent with the GeV upper limits. The only choice that satisfies both data was inverse Compton scattering oriented by very hard incident electrons ($\propto E^{-1.5}e^{\sqrt{E}/b}$; curve C), which may require another mechanism of reacceleration in the galactic halo.

Figure 2 shows a semilog plot of the differential flux of TeV gamma rays. Line E is the best-fitted exponential function ($\propto e^{-aE}$), and shows an agreement. The extrapolation to the GeV region is well below the EGRET upper limits.

The exponential function has a physical scale (in this case energy scale), and its contribution in the GeV region is negligibly small in the SED. The well-known physical process to obtain an energy scale is a fragmentation function $[(1/\sigma_h)(d\sigma/dx)$, where x is a Feynman $x]$ for such an inclusive particle spectrum as $e^+e^- \to q\bar{q} \to \gamma X$. It is typically to be fitted with the sum of the exponential functions. The fragmentation function of LEP data (e^+e^- collider experiment at the center of mass energy of ~90 GeV; Ackerstaff et al. 1998) was well fitted with the sum of three exponential functions:

$$\frac{1}{\sigma_h}\frac{d\sigma}{dx} = e^{5.5605-34.482x} + e^{3.1777-10.551x} + e^{7.2391-123.29x} \; .$$

Introducing the energy scale M_χ, the relationship between x

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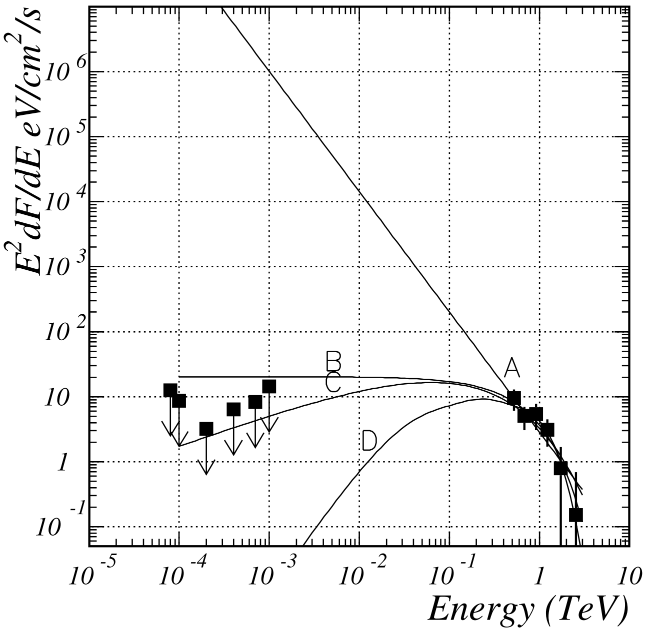

FIG. 1.—Spectral energy distribution. The high-energy data were obtained by CANGAROO-II and the low-energy upper limits by EGRET. The lines are the results of various fitting functions describe in the text.

and the energy of the gamma ray becomes $x = E/M_\chi$. The annihilation rate (F, in units of $\mathrm{cm^{-2}\ s^{-1}}$) and the energy scale were obtained by fitting the TeV gamma ray's spectrum with $(E/\sigma_h)d\sigma/M_\chi dx$ to be

$$F = (1.8 \pm 1.1) \times 10^{-11}\ \mathrm{cm^{-2}\ s^{-1}} ,$$
$$M_\chi = (3.0 \pm 0.6)\ \mathrm{TeV} ,$$

where we used the TeV gamma-ray fluxes from Table 6 in Itoh et al. (2003b). Note that these two parameters are highly anticorrelated, as described below. Here, F is the observed annihilation rate per unit area and time at Earth. The result is shown by line D in Figure 1. The χ^2 obtained in this fitting was 1.0, with 4 degrees of freedom. The EGRET upper limits are also cleared.

For the reaction of CDM to $\gamma\gamma$ (i.e., $\chi\chi \to \gamma\gamma$), a search for monochromatic gamma rays has been suggested (Bergström & Snellman 1988; Bouquet, Salati, & Silk 1989; Jungman & Kamionkowski 1995). The energy resolution of TeV gamma rays is approximately 35% (Table 5 of Itoh et al. 2003b). Curve F in Figure 2 is an example of a Gaussian ($\propto \exp\{-1/2[(E - M_\chi)/\sigma_E]^2\}$) with that resolution and a center value of 0.7 TeV.

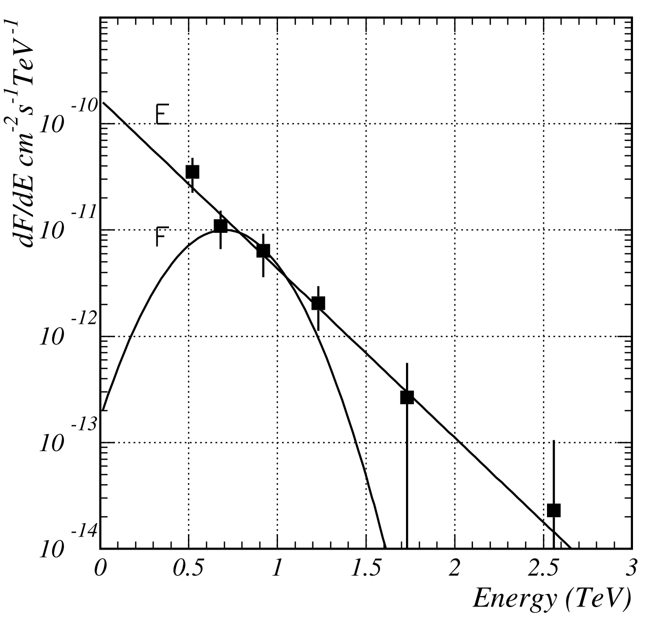

FIG. 2.—Differential flux of gamma rays from NGC 253 in the semilog scale. The data were obtained from CANGAROO-II. Line E is the best-fit exponential curve, and line F is an example of a Gaussian with an energy resolution of 35% and a center value of 0.7 TeV.

4. UPPER LIMIT FOR THE NUMBER DENSITY OF CDM

The annihilation in the volume of the halo 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 is the relative velocity of CDMs, $B_{q\bar{q}}$ is the branching fraction of $\chi\chi \to q\bar{q}$, n is the number density of CDM, V is the total volume of the halo, and d is the distance from Earth.

Here we consider the last volume-distance factor. The dark halo size of NGC 253 obtained by an H I measurement is 26.9 kpc (Puche & Carignan 1991), which corresponds to a solid angle of $\Delta\theta = 0\overset{\circ}{.}62$. Thus, the volume factor becomes $(d/3)(\Delta\theta)^3$, proportional to the distance. When we see the same–angular sized diffuse image, it suggests that distant objects have advantages. For example, comparing the Galactic center (distance of 8.5 kpc) and NGC 253, this factor becomes 300. Although the Galactic center may have a CDM concentration factor of, say, 1000 (Navarro, Frenk, & White 1996), it is highly model dependent. On the other hand, the total volume average of the squared density is less model dependent (only one factor changes under the assumption of r^{-n}, $n = 0, 1, \ldots$).

The annihilation cross section is another source of model dependences (for example, whether CDM is Dirac or Majorana fermions). Also, it depends on the details of particle physics, i.e., the details of SUSY breaking (Jungman, Kamionkowski, & Griest 1996). A much larger dependence is expected from the $\chi\chi \to \gamma\gamma$ process. In order to avoid it, we carried out the following adjustment. According to the Lee-Weinberg equation of the CDM density evolution (Lee & Weinberg 1977; Jungman et al. 1996), the annihilation cross section is directly related to the cosmological abundance, Ω_{CDM},

$$\Omega_{\mathrm{CDM}} = \frac{7 \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}}{\langle \sigma v \rangle} ,$$

which is mass independent. Recently, *Wilkinson Microwave Anisotropy Probe* determined $\Omega_{\mathrm{CDM}} = 0.23$ (Bennett et al. 2003). With this, we normalized $\langle \sigma v B_{q\bar{q}} \rangle$ to an order of $10^{-26}\ \mathrm{cm^3\ s^{-1}}$.

Now that all unknown factors have been filled, by fitting the TeV gamma rays spectrum with the described function, we can derive the best-fit density for CDM,

$$n = (2.4 \pm 0.6) \times 10^{-2} \sqrt{\frac{10^{-26}\ \mathrm{cm^3\ s^{-1}}}{\langle \sigma v B_{q\bar{q}} \rangle}}\ \mathrm{cm^{-3}} ,$$

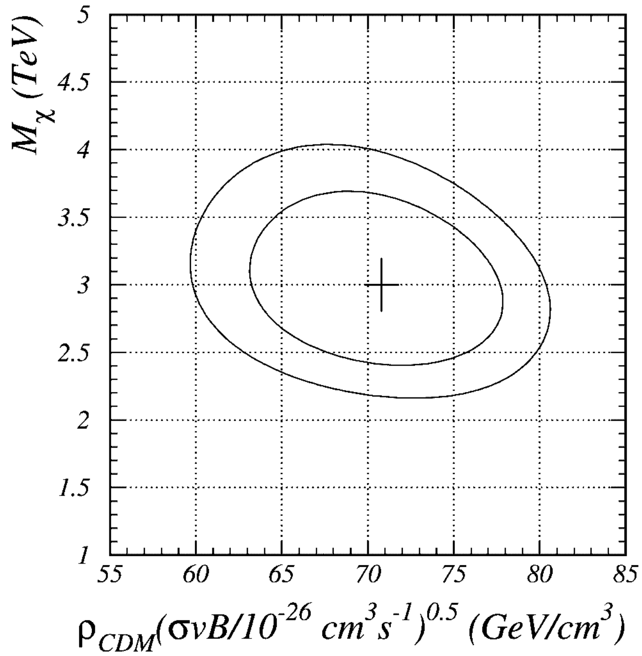

FIG. 3.—Correlation between M_χ and $\rho_{\rm CDM}$; 1 and 2 σ contours are shown, with the cross corresponding to the best-fitted value.

where n is still highly correlated with the M_χ value. Changing n to the energy density of the CDM,

$$\rho_{\rm CDM} = (70.8 \pm 7.4)\sqrt{\frac{10^{-26}\ {\rm cm^3\ s^{-1}}}{\langle\sigma v B_{q\bar{q}}\rangle}}\ {\rm GeV\ cm^{-3}}$$

is obtained, where the correlation between M_χ and $\rho_{\rm CDM}$ is shown in Figure 3. Note that n and $\rho_{\rm CDM}$ are the rms volume average of those densities. The lines are 1 and 2 σ contours. The errors became smaller compared to the value of F are because $\rho_{\rm CDM}$ is proportional to $\sqrt{F}$ and there is a strong anticorrelation between F and M_χ.

To summarize, the final fitting data and functions are

$$\begin{aligned}\frac{dF}{dE} &= \frac{F}{M_\chi}\left[\frac{1}{\sigma_h}\frac{d\sigma}{d(E/M_\chi)}\right]\\ &= \frac{\langle\sigma v B_{q\bar{q}}\rangle n^2[V/(4\pi d^2)]}{M_\chi}\left[\frac{1}{\sigma_h}\frac{d\sigma}{d(E/M_\chi)}\right]\\ &= \frac{\langle\sigma v B_{q\bar{q}}\rangle \rho_{\rm CDM}^2[V/(4\pi d^2)]}{M_\chi^3}\left[\frac{1}{\sigma_h}\frac{d\sigma}{d(E/M_\chi)}\right],\end{aligned}$$

where $(1/\sigma_h)\{d\sigma/[d(E/M_\chi)]\}$ should be replaced with the linear combination of three exponential functions described so far, and dF/dE is given in Table 6 of Itoh et al. (2003b) and Figure 1 of Blom et al. (1999), respectively.

Although these values are the best-fit ones, there are not enough reasons to insist that this is evidence for CDM other than that the energy spectrum was well fitted with the exponential function. This value should be considered to be an upper limit. We therefore carried out a scan for various M_χ assumptions and obtained upper limits versus M_χ. The results are shown in Figure 4. Considering the dynamic range of the fragmentation function measurements, the searched range was selected to be from 0.5 to 50 TeV. In the figure, the 2 σ upper limits are shown. The improvement below 0.65 GeV was due to the EGRET upper limits.

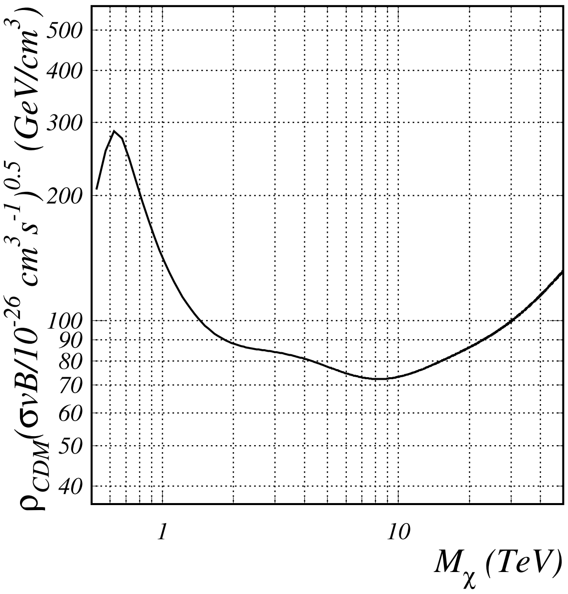

FIG. 4.—Plot of 2 σ upper limits of $\rho_{\rm CDM}$ vs. M_χ for various M_χ assumptions.

In addition, we carried out a search for monochromatic gamma rays in the energy region between 0.5 and 3 TeV. The TeV gamma-ray energy spectrum was fitted with Gaussians under various peak-energy assumptions. A uniform energy resolution of 35% was assumed. A typical line is shown in Figure 2 (line F). The 2 σ upper limits for the mass densities of CDM, $\rho_{\rm CDM}[\langle\sigma_{\gamma\gamma}v\rangle/(10^{-29}\ {\rm cm^3\ s^{-1}})]^{1/2}$, were obtained (Fig. 5). Here we used a smaller normalization factor for $\langle\sigma_{\gamma\gamma}v\rangle$, as was expected from the particle theory (Bergström & Snellman 1988). These upper limits are higher than those in Figure 4.

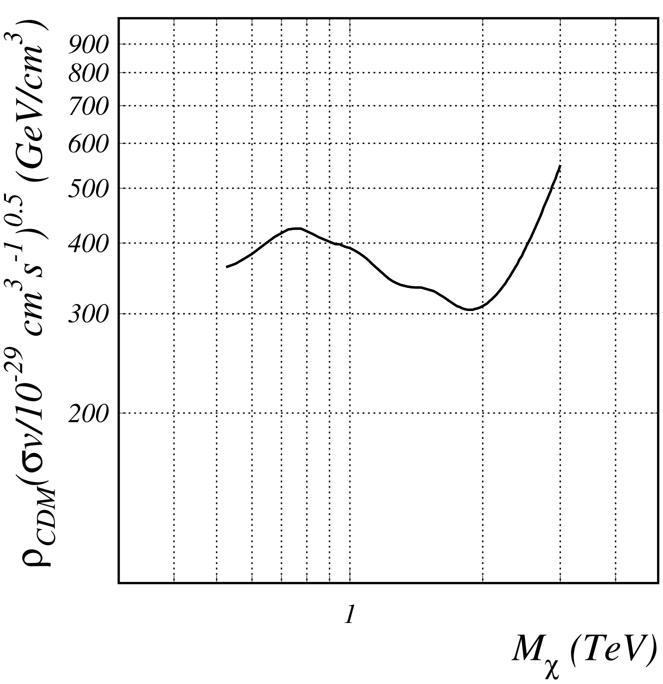

FIG. 5.—Upper limits of $\rho_{\rm CDM}$ vs. M_χ. Here, a monochromatic gamma-ray search was carried out for the reaction $\chi\chi \rightarrow \gamma\gamma$.

5. DISCUSSION

The halo density estimated by the H I studies is 0.015 $M_\odot$ pc^{-3} (0.57 GeV cm^{-3}; Puche & Carignan 1991), which is 2 orders of magnitude lower than our upper limits. The gamma-ray flux from NGC 253 should be explained by the standard cosmic-ray theory. Because of the starburst phenomena, we could not discard a cosmic-ray interpretation (Völk, Aharonian, & Breitschwerdt 1996). If the cosmic-ray emission is accurately determined from the study of the multiwavelength spectrum, this upper limit will be greatly reduced to the error bar level.

A scan of the nearby galaxies that are not starburst will be promising in the search for CDM. The Sculptor group is an especially interesting target, also suggested by an H I measurement (Puche & Carignan 1991).

The search for gamma rays from massive galaxies is considered to reduce the upper limit for the galactic density of CDM. Ten times heavier astronomical objects that are nearby would give a sensible result. For example, M87 is considered to be more than 10 times heavier than our Galaxy (Baltz et al. 2000). The distance is several times farther than NGC 253. The volume-distance factor, $(d/3)(\Delta\theta)^3$, is therefore an order of magnitude lower than our case (reported $\Delta\theta < 0\overset{\circ}{.}127$ by Aharonian et al. 2003a). On the other hand, the recent observation with HEGRA reported about a 10 times fainter gamma-ray intensity (Aharonian et al. 2003a). These values should result in the same magnitude of CDM density, while M87's density is considered to be larger than that of NGC 253. Publication of the differential flux of the TeV gamma ray from M87 is awaited.

Although M31 is also massive, the apparent size is larger than the field of view of the IACT, which requires special treatments for background subtractions (Aharonian et al. 2003b).

Considering a figure of merit (FOM) for the CDM search, we should consider the total mass of the galaxy, the volume of the halo, distance, and visible size simultaneously. The CDM density might be proportional to the total mass (M_G) divided by the volume. Thus, the expected gamma ray flux should be proportional to $\mathrm{FOM} = M_G^2 d^{-5}(\Delta\theta)^{-3}$. We selected those nearby galaxies that have a visible size between 3×10^{-3} and 10^{-2} radians (a favorable size for the IACT measurements). NGC 5128 (Cen A) and NGC 5236 (M83) were calculated to have a bigger FOM than that of NGC 253. Especially for Cen A, a flux 100 times larger is expected.

We also applied the same discussion to ω Centauri (Guy et al. 2003). A dark matter origin of globular clusters was proposed by Peebles (1984). The distance is close, and a lower cosmic-ray level is expected. The FOM was calculated to be 10,000 times higher than that of NGC 253. An upper limit of the same order as the baryonic density could be obtained.

A high-sensitivity search in the Galactic center is also awaited (Tsuchiya et al. 2002). However, removing the model dependence and estimating the cosmic rays there are keys for this case.

As opposed to the accelerator experiment, only IACT measurements are sensitive to CDM with a mass heavier than TeV. The two experiments are complementary to each other.

6. CONCLUSION

A constraint on the cold dark matter (CDM) was obtained using the data of the gamma-ray halo around the nearby starburst galaxy NGC 253. Upper limits for the CDM density were obtained in the mass range between 0.5 and 50 TeV. Although this limit is higher than the expected value, this is one of first trials from the IACT observational side. The IACTs have been proven to be able to detect it. The presently existing IACTs are competitive devices compared with high-energy particle accelerators. The nearby galaxies, such as NGC 5128 (Cen A) and NGC 5236 (M83), and/or globular cluster ω Centauri will be next interesting targets. Observational searches for probable candidates should be systematically continued.

We thank J. Hisano and M. Fukugita of ICRR for various discussions.

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