Galactic Gamma-Ray Halo of the Nearby Starburst Galaxy NGC 253

T. Yoshida,[1] T.G.Tsuru,[2] C. Itoh,[3] R. Enomoto,[4] and S. Yanagita,[1]
(1) Ibaraki University, Mito, Ibaraki 310-8512, Japan
(2) Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
(3) Ibaraki Prefectural Univ. of Health Sciences, Ami, Ibaraki 300-0394, Japan
(4) Inst. for Cosmic Ray Res., Univ. of Tokyo, Kashiwa, Chiba 277-8582, Japan

Abstract

The CANGAROO-II telescope detected diffuse TeV gamma-ray emission from a nearby edge-on starburst galaxy NGC 253. We present a halo model of the nonthermal emissions due to synchrotron radiations and inverse Compton scatterings. This model successfully explains the multiwavelength spectrum of NGC 253. We discuss propagation of cosmic-ray electrons into the halo and acceleration of electrons due to the galactic wind.

1. Introduction

The CANGAROO-II imaging atmospheric Cherenkov telescope has detected TeV gamma-ray emission from a nearby edge-on starburst galaxy NGC 253 [5, 6]. The size of the emitting region is similar to, or larger than, the optical size 0.3° of NGC 253. This is the first detection of TeV gamma-rays from a normal-sized spiral galaxy like our Galaxy.

The acceleration and propagation of galactic cosmic rays (GCRs), which are observed directly near the earth, are among the big topics in physics and astrophysics. The distribution of GCR with an energy of less than ∼10 GeV in the Galaxy has been surveyed by tracing diffuse gamma rays[4]. The resultant distribution of diffuse gamma rays has been argued based on the scenario of the SNR origin of GCR. In the TeV energy range searches for diffuse gamma-rays in our Galaxy have also been carried out to obtain the spatial distribution of TeV cosmic rays. It is, however, difficult to detect diffuse TeV gamma rays due to the limitations of the present techniques. Obviously, we can learn how high-energy particles are accelerated and propagate on the galactic scale from the observations of NGC 253 by TeV gamma-rays.

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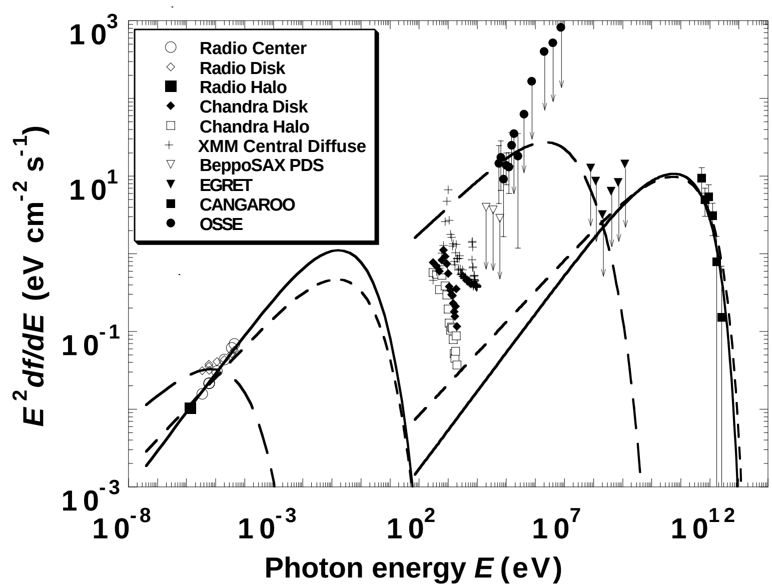

Fig. 1. Multiband spectrum of NGC 253. The closed squares were obtained by CANGAROO-II. The X-ray data were corrected for photo-absorption in both the Galaxy and NGC 253, except that no correction was applied to the BeppoSAX hard X-ray data. The lines shown were obtained by estimations described in the text.

2. Inverse Compton Emission Halo Model

In Fig. 1 we summarize multiwavelength spectrum from radio to TeV energies of NGC 253. We first discuss the emission mechanism at gamma-ray energies from the multiwavelength spectrum. Goldshmidt & Rephaeli[3] reported that the gamma-ray emission detected by OSSE (the closed circles in Fig. 1) was attributed to the Inverse Compton Scattering (IC) of ubiquitous far-infrared(FIR) photons from dusts observed around the center of the galaxy. However, a simple extrapolation to the GeV range exceeds the 2 σ upper limit of 3.4×10^{-8} cm^{-2} s^{-1} [1] obtained by EGRET (the closed triangles). The multiwavelength spectrum suggests that the origin of TeV gamma rays should be different from that of sub-MeV gamma rays.

The very large radio halo of ~ 9 kpc [2] would suggest the existence of a population of very high-energy electrons which emit our TeV gamma-rays other than those concentrated near to the central or disk region of the galaxy. There are also sure target photons for IC, such as CMB as well as very abundant FIR photons. Here, we quantitatively examine whether these electrons and photons are responsible for TeV emissions.

We assume that the total number spectrum of electrons at the source has the following form $N_e(\gamma) = N_{e0}\gamma^{-p}\exp(-\gamma/\gamma_m)$, where N_{e0} is an electron density factor, γ the Lorentz factor, and γ_m the maximum Lorentz factor of the electrons (a cutoff), respectively. We take the FIR photon spectrum model, in which the dust absorption efficiency is proportional to the photon frequency, as described in [3]. Here, we assume that the photon field is isotropic. The energy density of the photon field $U_{\rm IR}$ at radius R_s is approximated as $U_{\rm IR} = L_{\rm IR}/(\pi R_s^2 c)$. We simply adopt the average value of $U_{\rm IR}$ in a spherical region with a size of R_s as the photon density. The volume-averaged photon density ($< U_{\rm IR} >$) is $3U_{\rm IR}(R_s)$. Assuming the value of the electron spectrum index p, we could determine the two parameters $N_{e0}/(4\pi D^2)$, where D is the distance to the source, and γ_m for the electron spectrum as fitting the CANGAROO-II flux and keeping the EGRET upper limit.

Here, we adopt $R_s = 10$ kpc, suggested by the size of TeV emitting region[5, 6], with an assumption of a cosmic-ray halo. We considered two populations of photons as the target of the IC process, IR and CMB. The energy densities for each population are $< U_{\rm IR} >= 1.6$ eV cm^{-3} and $U_{\rm CMB} = 0.26$ eV cm^{-3}, respectively. In Fig. 1, the solid and dashed lines represent the synchrotron and IC emission models with the power-law index of the electrons $p = 2$ and 2.2, respectively. Here, the value of p was chosen based on constraints by the shock acceleration ($p \geq 2$) and reconciliation between the EGRET upper limits and the CANGAROO-II TeV results. The fluxes of the TeV gamma-rays and the upper limit of EGRET restricted the parameter choices of the electron spectrum: $N_{e0}/(4\pi D^2) = 6.8 \times 10^8$ cm^{-2} and $\gamma_m = 2.5 \times 10^6$(1.3TeV) for $p = 2$, and $N_{e0}/(4\pi D^2) = 8.4 \times 10^9$ cm^{-2} and $\gamma_m = 3.6 \times 10^6$(1.9TeV) for $p = 2.2$, respectively. We find the total energies and average energy densities of the electrons within $R_s = 10$ kpc to be 5.9×10^{54} erg and 0.03 eV cm $^{-3}$ for $p = 2$, and 2.4×10^{55} erg and 0.12 eV cm $^{-3}$ for $p = 2.2$, respectively. The strength of the magnetic field (B) were estimated to be 2.5μG for $p = 2$, and 1.7μG for $p = 2.2$, respectively, by adjusting the calculated synchrotron emissions to the radio halo data.

The halo model, however, cannot explain observed emissions in the keV-MeV energy region. Goldshmidt & Rephaeli[3] introduced the IC model with a very localized FIR and high-energy electrons in order to explain the OSSE result. We could reproduce the OSSE flux by adopting an average photon density of $< U_{\rm IR} >= 1.8 \times 10^3$ eV cm^{-3} within $R_s = 0.3$ kpc, and taking the following parameters of the electron spectrum: for example, in case of $p = 2.3$, $N_{e0}/(4\pi D^2) = 4.5 \times 10^9$ cm^{-2} and $\gamma_m = 1.2 \times 10^4$(6.2 GeV). The total energy and average energy density of the electrons are 8.5×10^{54} erg and 1.6×10^3 eV cm $^{-3}$, respectively. Such a high density and low cutoff energy may be reasonable, considering the starburst characteristics and FIR density around the center of this galaxy. This is also consistent with the EGRET upper limits, as shown in Fig. 1(the long-dashed line).

In the halo model, the electron energy density was obtained to be 0.03 $\sim$ 0.12 eV cm^{-3}, which is one order higher than that of our Galaxy. If we assume the proton to electron ratio to be 100, this implies that the total energy of cosmic rays in NGC 253 may amount to $5.9 \times 10^{56} \sim 2.4 \times 10^{57}$ergs, which is one hundred-times higher than that for our Galaxy. The starburst age and the supernova rate in NGC 253 were estimated to be $\sim 10^7$yr and ~ 0.3yr^{-1}, respectively. The starburst activity characterizing NGC 253 may explain the large amount of total energy of cosmic rays.

3. Propagation and Acceleration

The high-energy electrons in the halo of the galaxy explain most of multi-band spectrum of NGC 253 quite well. The biggest question is whether high-energy electrons can propagate out to a distance of $\sim$ 10kpc from the disk of the galaxy without any severe energy losses. Electrons may diffuse out to a distance of $R_L \sim 2(\kappa t_{cool})^{1/2}$ within their cooling time (t_{cool}) due to synchrotron and IC losses. When the diffusion coefficient of electrons (κ) of order $3 \times 10^{29}(E/\mathrm{GeV})^{0.6}\mathrm{cm}^2\mathrm{s}^{-1}$ is used, we found that electrons of 1 TeV which emit sub-TeV gamma-rays can propagate to a distance of $\sim$ 9 kpc.

The diffuse X-ray emission extending from the nuclear region toward the halo is considered to be due to the galactic wind. A galactic wind running freely along the galactic minor axis may have been formed around 10^7yr after the start of the starburst activity. Wind with a velocity of $2000 \sim 3000$km s^{-1} finally hits the ambient cool gas and forms a shock in the halo. This shock in the halo may accelerate particles by the Fermi process. The maximum energy of electrons accelerated by this process is estimated to be $8 \sim 25$ TeV if we assume a shock velocity of $\sim$ 2000km s^{-1}, a magnetic field of 2 μG, and a starburst age of $\sim 10^7$ yr by equating the acceleration rate with the cooling rate due to the synchrotron and IC losses. Another possibility of particle acceleration in the termination shock of the galactic wind has been proposed by Jokipii & Morfill[7]. These two cosmic-ray acceleration processes may be related to the rather hard spectrum required for the electrons in the halo.

4. References

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