Detection of diffuse TeV gamma-ray emission from the nearby starburst galaxy NGC 253

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Abstract

We report TeV γ-ray observations of the nearby normal spiral galaxy NGC 253. NGC 253 is one of the nearest starburst galaxies, at a distance of $\sim$2.5 Mpc. This relative closeness, coupled with the high star formation rate in the galaxy, make it a good candidate TeV γ-ray source. Observations were carried out in 2000 and 2001 with the CANGAROO-II 10 m imaging atmospheric Cherenkov telescope. TeV γ-ray emission is detected at the $\sim 11\sigma$ level with a flux of $(7.8 \pm 2.5) \times 10^{-12}$cm^{-2}sec^{-1} at energies >0.5 TeV. The data indicate that the emission region is broader than the point spread function of our telescope.

1. Introduction

NGC 253 is a nearby starburst galaxy, in which a high cosmic-ray density is expected [1]. The large-scale radio continuum structure of NGC 253 was studied by [2] and Carilli et al.found a large, bright synchrotron-emitting halo extending to more than 10 kpc from the centre [3]. Diffuse X-ray emission from the halo has also been detected [4, 5]. The OSSE instrument on the CGRO detected sub-MeV γ-rays [6] which were interpreted to be attributed to FIR photons scattered by the high energy, synchrotron emitting, electrons [7]. While the EGRET detector gave only upper limits on γ-ray emission in GeV energies [8]. We have observed NGC 253 with the CANGAROO-II telescope in 2000 and 2001. The observations of NGC 253 provide the opportunity to study the distribution of cosmic rays in galaxies like our own, while the detection of diffuse TeV emission from our Galaxy is technically very difficult (e.g., [9]).

pp. 1–8

2. Observation and Analysis

A total of ∼75 hours of observations ("ON") were made, with a similar amount of background ("OFF") observations. Each ON-source run tracked the center of NGC 253 through its highest elevations, with OFF-source observations offset in right ascension made in order to estimate the background. An edge-on galaxy, NGC 253 appears optically as a disc $\sim 0.4^\circ$ by $\sim 0.1^\circ$ in size. This is larger than our angular resolution, but much smaller than the telescope's FOV. After selecting data taken at high elevation angles ($> 70^\circ$) in good weather conditions, a total of 2959 min. ON-source and 2417 min. OFF-source data remained for further analysis.

First, "cleaning" cuts were applied to the camera images, requiring pixel pulse-heights of greater than ∼3.3 photoelectrons, Cherenkov photon arrival times within 40 nsec, and clusters of at least four adjacent triggered pixels in each event. After these pre-selections, we carried out a shower image analysis using the standard set of image parameters, distance, length, width, and α [10], combining length and width (after an initial distance cut) to assign likelihoods to each event [11, 12]. The likelihood for both a γ-ray origin and cosmic-ray proton origin were calculated. The cut to reject background events was based on the ratio of these two likelihoods. After these cuts, the image orientation angle (α) was plotted. A γ-ray signal appears as an excess at low α after the normalized OFF-source α distribution is subtracted from the ON-source distribution. As shown in Fig. 1.a, an excess of events with $\alpha < 30^\circ$ is clearly observed for NGC 253. The number

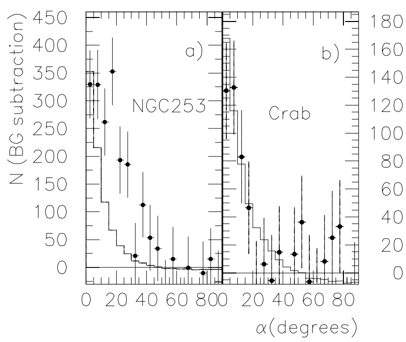

Fig. 1. Distributions of the image orientation angle (α): a) for NGC 253 and b) for the Crab. The points with error bars were obtained by subtracting the normalized off-source data from the on-source data. The ratio of events in the higher α ($> 30^\circ$) regions for on- and off-source data was used as the normalization factor, which agreed with the ratio of observation times to within 2%. The histograms were obtained from Monte Carlo simulations of γ-rays from a point-source.

of γ-ray-like events is 1652±149 (11.1σ), corresponding to 0.56 γ-rays per min.

The same analysis procedure was applied to Crab nebula data from observations in November and December 2000 as a check. Approximately 10 hours of good data were obtained. The resulting α plot, shown in Fig. 1.b, has an excess of 393±59 events (6.7σ). The solid histograms are the Monte Carlo predictions for the α distribution in the case of a point source. Note that the Crab observation was carried out at large zenith angles, around 56°. At such large zenith angles, the α distribution deteriorates due to the shrinkage of Cherenkov images. In order to compensate for this, we applied tighter cuts in the Crab analysis. As a result, the α distribution for Crab is slightly wider than that for NGC 253 (which is observed near the zenith). The experimental result, however, agrees with the Monte Carlo prediction in case of the Crab observation. For NGC 253, the α distribution is broader than the PSF by a factor of two. Our Monte Carlo simulations predicted that 73% of events from a point source would have $\alpha < 15°$, whereas in fact 56% of events were contained within this range.

3. Results

The spatial distribution of the γ-rays from NGC 253 was studied using the so-called significance map. The thick solid contours in Fig. 2. are our results. The 65% confidence level contour, which is roughly one standard deviation of

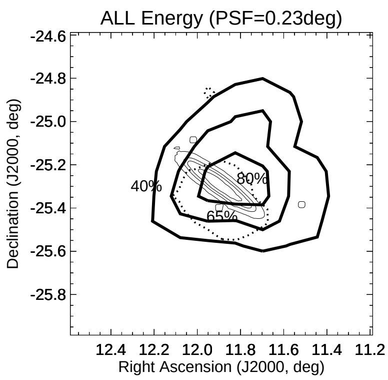

Fig. 2. Profile of the emission around NGC 253. The solid thick contours were obtained from our observations. This was made from the distribution of the detection significance determined at each location from the differences in the α plots (ON- minus OFF-source histogram) divided by the statistical errors. The solid thin contours are the DSS2 data. The dotted contour was obtained with the CANGAROO-II telescope for the Crab nebula.

our angular resolution, is shown and compared with an optical image from DSS2, which is shown by the solid thin contours. The size of the TeV emission region is of the same order as the optical image, or larger. The dotted contour is the 65%-contour obtained by the Crab observation. It is consistent with the Monte Carlo prediction of 0.25°. That of the near-zenith observations was estimated to be 0.23°. The γ-ray acceptance of the telescope gradually decreases beyond 0.3° from the center of the field of view (dropping to half at 0.8°), and so we are unable to make a more detailed morphological study. It is clear, however, that the observed γ-rays distribution from NGC 253 is inconsistent with emission from a point source. In order to derive the spectrum of NGC 253 self-consistently, we adopted an iteration method. At first we used an acceptance calculated by the simulation with a $E^{-2.5}$ spectrum and we obtained the index of -3.7 ± 0.3. We then used this fitted value in the simulations to re-derive the spectrum. This process rapidly converged at an index of -3.75 ± 0.27. The same iterative procedure was carried out using a function with cutoff. It also showed a good convergence. The differential fluxes obtained in 2000 and 2001 agreed within these errors. The differential fluxes are plotted in the spectral energy distribution (SED) shown in Fig. 3., together with measurements from other energy bands [2-6, 8] .

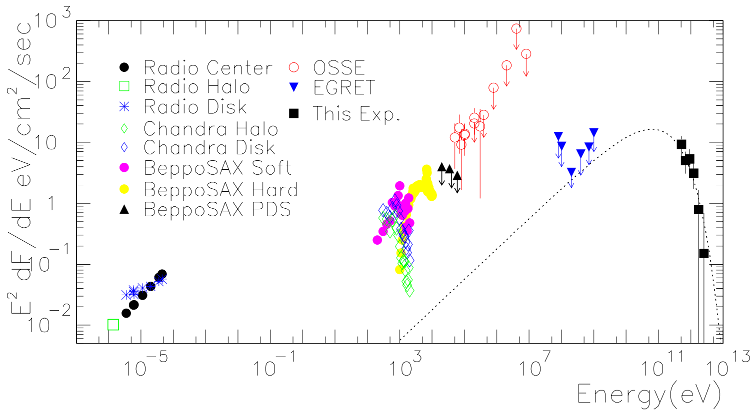

Fig. 3. Multi-band spectrum of NGC 253. The black squares were obtained by this experiment. When we constrain the flux to 3/4 of the EGRET upper limit [8] at 0.2 GeV using the function in the text, a flux proportional to $E^{-1.5}e^{-\sqrt{E}/(0.25\pm0.01)}$ was obtained with χ^2/DOF=1.8/5 (the dotted line). The X-ray data for CHANDRA and BeppoSAX soft component were corrected for photo-absorption in the Galaxy, but no correction was applied to the BeppoSAX hard X-ray data. No correction was made for photo-absorption inside NGC 253 itself. We note that the BeppoSAX, OSSE, and EGRET data were not able to spatially resolve NGC 253, in contrast to the other data.

A simple power-law fit to the TeV spectrum of NGC 253 deviates greatly from the EGRET measurements at GeV energies [8]: a turn-over below the TeV region clearly exists. We fitted a power law with an exponential cut off, fixing the power-law index to −1.5, i.e., an inverse Compton–like spectrum (where the exponential term is $\exp(-\sqrt{E}/a)$, with a a free parameter). The resulting improved fits are shown by the dotted curve in Fig. 3.. The minimum power-law index providing an acceptable fit (based on the χ^2 value) was −1.8 (2σ limit). If the observed γ-rays are produced by inverse Compton scattering of cosmic microwave background (CMB) photons, then the fitted spectrum suggests that the maximum energy of the parent electrons is around several TeV. The integral flux is estimated to be $(7.8 \pm 2.5) \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at energies greater than 0.52 TeV.

4. Discussions

The observations reported here are the first detection of TeV γ-rays from a normal spiral galaxy (other than our own), and reveal the emission to be spatially extended and temporally steady. NGC 253 has been observed over a range of photon energies, as depicted in Fig. 3., however the SED is more difficult to interpret. The emission of 50–200 keV photons observed by OSSE [6] was interpreted as being inverse Compton scattering of far-infrared photons from dust in the central region [7]. A simple extrapolation to higher energies exceeds the EGRET 2σ upper limit [8]. Clearly, it is not possible to explain the OSSE and CANGAROO-II observations and the EGRET upper limits by invoking inverse Compton emission from a single population of electrons. The very large radio halo, extending over ∼10 kpc [2, 3] and up to X-ray energies [4], suggests the existence of a population of very high-energy cosmic rays which may be responsible for the inverse Compton production of TeV γ-rays [13], quite separate from sources concentrated near the centre of the galaxy which might emit the majority of the photons observed by OSSE.

5. Conclusion

NGC 253 is the first of a new class of object to be detected at TeV energies. The extended and steady nature of the emission makes it clear that the TeV γ-rays are produced in a different environment than that of previously reported extragalactic sources of the active galactic nucleus class. Studies of NGC 253 will, like those of the LMC at GeV energies [14], provide the opportunity to learn more about the cosmic ray environment in galaxies like our own.

6. Acknowledgements

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7. References

[1] Voelk, H.J., Aharonian, F.A., & Breitschwerdt, D. 1996, Space Sci. Rev., 75, 279
[2] Hummel, E., Smith, P., & van der Hulst, J.M. 1984, A&A, 137, 138
[3] Carilli, C.L., Holdaway, M.A., Ho, P.T.P., & de Pree, C.G. 1992, ApJ, 399, L59
[4] Cappi, M., Persic, M. Bassani, L., et al. 1999, A&A, 350, 777
[5] Strickland, D.K., Heckman, T.M., Weaver,K.A., Hoopes, C.G., & Dahlem, M. 2002, ApJ, 568, 689
[6] Bhattacharya, D., The, L.-S., Kurfess, J.D., et al. 1994, ApJ, 437, 173
[7] Goldshmidt, O. & Rephaeli, Y. 1995, ApJ, 444, 113
[8] Blom, J.J., Paglione, T.A.D, & Carramiñana, A. 1999, ApJ, 516, 744
[9] Aharonian, F.A., Akhperjanian, A.G., Barrio, J.A., et al. 2002, Astropart. Phys., 17, 459
[10] Hillas, A.M. 1985, Proc. 19th ICRC (La Jolla), 3, 445
[11] Enomoto, R., Hara, S., Asahara, A., et al. 2002, Astropart. Phys., 16, 235
[12] Enomoto, R., Tanimori, T., Naito, T., et al. 2002, Nature, 416, 823
[13] Itoh, C., Enomoto, R., Yanagita, Y., Yoshida, T., & Tsuru, T.G. 2002, in preparation.
[14] Sreekumar, P., Bertsch, D.L., Dingus, B.L., et al. 1992, ApJ, 400, L67