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Study of the IC443 SNR with the Fermi LAT

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ABSTRACT

During the first six months of data taking the Fermi satellite was capable to detect gamma ray emission of the nearby supernova remnant IC443 (G189.1+3.0). IC443 is a shell-type supernova remnant located in the anticenter region where observation can be made clean enough from possible foreground and background overlap, even though care has to be taken due to the vicinity of one of the brightest gamma-ray pulsars, Geminga. IC443 estimated age (20–30 kyr) and the observed two-shell morphology with different radii suggest that the SNR shell has been interacting with surrounding interstellar matter and a neighboring SNR shell. Also the detection of strong molecular emission lines and TeV gamma-ray emission support the idea that the blast has been interacting with dense molecular gas accelerating cosmic-ray particle. After the first year of data taking, Fermi will be surely capable to determine the spatial extension and resolve in much finer details the spectral shape of the gamma-ray emission produced by the accelerated cosmic rays in IC443 distinguished from those of galactic origin.

1. The IC443 in the past

1.1. Radio optical and X campaigns

IC443 is one of the most interesting SNRs known, presenting strong molecular emission lines that makes it one of the clearest cases for a supernova blast interaction with molecular clouds, and one of the best candidates for the connection between SNRs and HE cosmic ray sources [1]. This very interesting source has been deeply investigated in the past at different wavelengths: what emerged was that IC443 is an asymmetric shell-type SNR with a diameter of about 45 arc minutes [2] and a medium age of about 3×10^4 years [3–5]. From optical images and radio maps [6–8] two half shells appear maybe due to the interaction of the shock fronts with the molecular environments which may present different densities. IC443 is also included in Green's catalog (2004) as one of the brightest source at 1 GHz with a spectral index of 0.36 and a flux density of 160 Jy. IC443 is also bright in X-rays, and it has been observed by Rosat [9], ASCA [10], XMM [11–15] and Chandra [16]. The XMM observations claimed the presence of 12 X-ray sources, all located in the relatively small region of SNR blast molecular cloud interaction clearly visible also in radio [11].

Concerning the molecular material IC443 has been interacting with, some studies [17,8,11] demonstrate the existence of a total mass of 1.1×10^4 Solar Mass, mainly located in a quiescent cloud in front of the remnant (with linear scales of a few parsecs and densities of a few hundred particles per cm^3) which is absorbing optical and X-ray radiation, with an additional mass estimated approximately of 500–2000 Solar Mass [18] being directly perturbed by the shock in the northern region of interaction, near the SNR, where the X-ray sources are located and the radio emission is louder.

1.2. High and very high energy gamma rays observations

EGRET detected a gamma-ray source above 100 MeV, co-spatial with the SNR, named 3EG J0617+2238 [19], presenting a flux of $(51.4\pm3.5)\times10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}\,MeV^{-1}}$ and a photon spectral index of 2.01 ± 0.06. In the work of Lamb & Macomb 1997, an independent analysis of GeV photons showed the GeV source J0617+2237, also co-spatial with the 3EG J0617+2238, at the center of the SNR. In the VHE range, the MAGIC telescope [20] discovered the J0616+225 source. The interesting result of this discover is that the source is displaced with respect to the position of the EGRET source, and coincident with the most massive molecular cloud in the SNR vicinity, as measured by ^{13}CO and ^{12}CO emission maps. These results have been also confirmed by observations of the VERITAS array [21]. The spectrum has been fitted with a simple power law function with an integral flux of

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$(1.0\ \pm 0.2)\times 10^{-11}$ $(E/0.4\,\text{TeV})^{3.1\pm 0.3}\,\text{cm}^2\,\text{s}^{-1}\,\text{TeV}^{-1}$, with quoted errors being statistical and systematic errors estimated to be 35% in flux and 0.2 in spectral index. To conclude the HE and VHE energy results claimed, the 3EG J0617+2238, the GeV J0617+2237, and MAGIC J0616+225 positions can be considered all inconsistent with that of the pulsar wind nebula (PWN) CXOU J061705.3+222127 [22].

2. IC443 with Fermi

2.1. The Fermi satellite

The Fermi satellite, consisting of the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT), was launched on 11 June 2008 into a low Earth circular orbit at an altitude of 565 km and an inclination of 25.6°. The LAT [23] is a pair-production telescope with large effective area ($\sim$8000 cm^2) and field of view (2.4 sr), sensitive to gamma rays between 30 MeV and $>$300 GeV. The LAT began normal science operations on 11 August 2008, and since then has been working mostly in survey mode, scanning the entire gamma-ray sky every 3 h. The overall sensitivity of the LAT is about 25 times that of EGRET, while the angular resolution is also significantly improved (it ranges from 3° to 6° at 100 MeV to $\sim$0.1–0.2° at 100 GeV). The mission was designed with a five year lifetime and a goal of at least 10 years of operations. The scientific goals of the mission include understanding of particle acceleration in Active Galactic Nuclei (AGN), pulsars, and supernova remnants (SNRs), exploring the high energy emission of Gamma-ray Bursts (GRB), and probing the nature of dark matter.

After 6 months of data taking the Fermi sky looks like in Fig. 1. It is clearly visible the first discovery of the Fermi LAT due to its excellent timing performance, the CTA1 pulsar [24], together with some very bright galactic pulsars (Vela, Crab and Geminga) and extragalactic gamma ray emitters (i.e. 3C454.3), and also the IC443, located approximately in the anticenter region, almost between Crab and Geminga pulsars.

2.2. The data analysis

To have preliminary informations about the spectrum shape and count maps, a region of interest of 15° has been selected centered at the IC443 maximum likelihood position. The *gtfindsrc* Fermi Science Tool has been run and the best position obtained was 94.31 and 22.56 for right ascension and declination, respectively, with an error radius of 0.01°. Fig. 2 shows the 15° ROI. The 15° radius has been chosen in order to have information on the flux at 100 MeV. The Fermi PSF is quoted to be about 5° at 100 MeV and 0.3° at 100 GeV. The count map shown is convolved with the PSF, at 100 MeV also displayed in the figure. In Fig. 2 the CRAB are clearly visible, indicated as 0FGL J0534+2256 in the Fermi bright source list paper [25], Geminga as 0FGL 0634+1745 and a bright gamma ray source coincident with the IC443, the 0FGL J0617+2234.

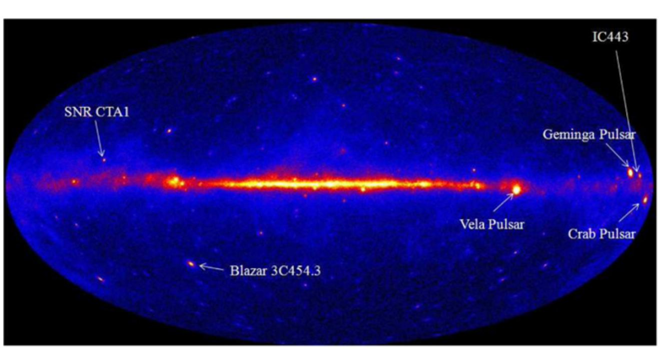

Fig. 1. Fermi 6 months all sky.

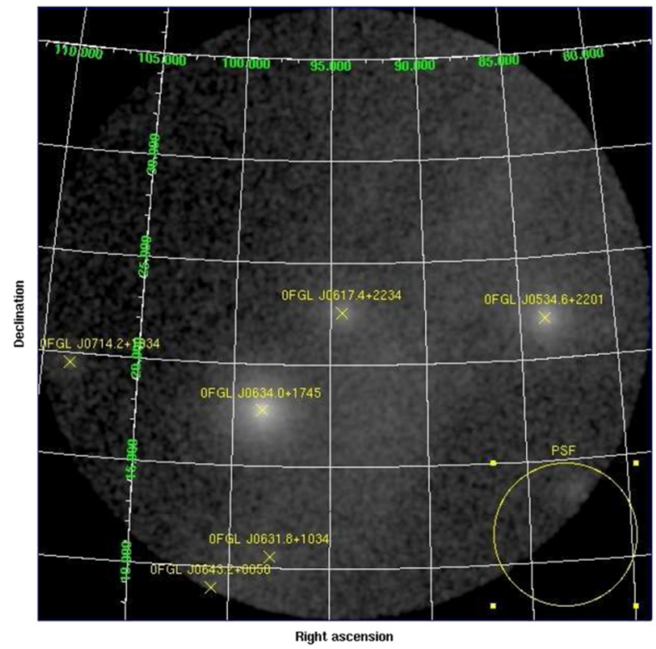

Fig. 2. IC443 15° ROI for a photon energy range 100 MeV–100 GeV.

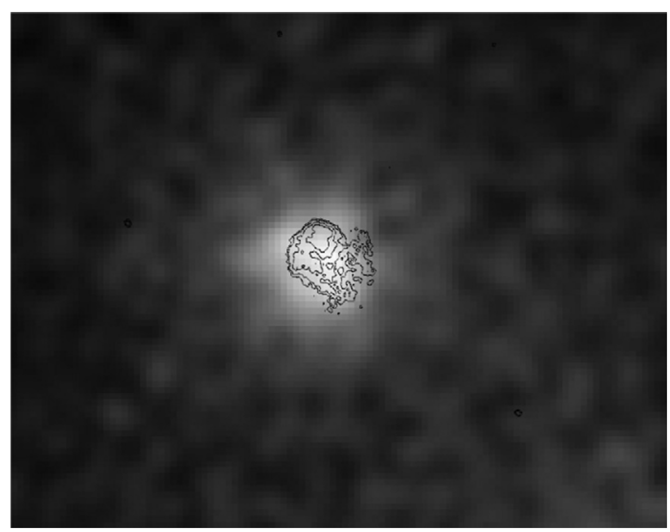

Fig. 3. Zoom of the IC443 count map with Fermi data. The ROSAT contours are also superimposed.

Fig. 3 is a zoom of the previous image. A ROI of 3° has been chosen in order to better compare the Fermi image with the *jelly fish* ROSAT contour, which is superimposed.

Another count map (Fig. 4) has been done with a different energy threshold fixed at 5 GeV. Also this count map is PSF convolved but at 5 GeV the PSF is about 0.5° (shown in figure). From a simple visual inspection of both images, it is not easy to infer anything about a possible extension of the gamma ray emission region, even applying a higher energy cut where the pointing power of the Fermi satellite is better. More precise results concerning the extension will be obtained with more statistics (one year data taking) and using also simulations support.

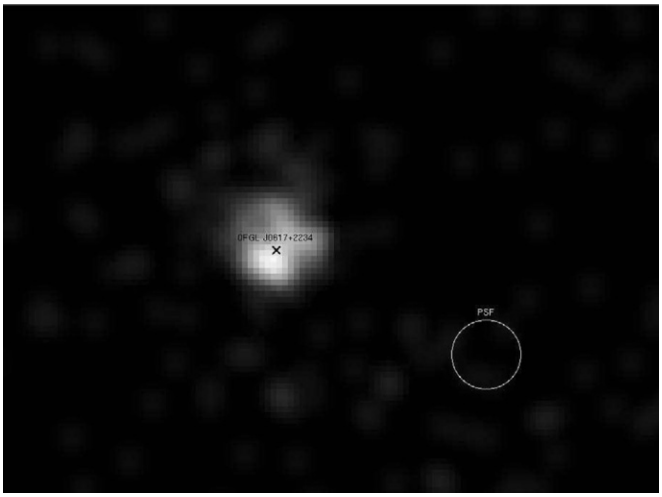

Fig. 4. IC443 zoom above 5 GeV.

For computing the spectral shape of the gamma ray emission in the point-like hypothesis, the unique results obtainable with the first 6 months data, two different and complementary techniques have been used: the maximum likelihood *gtlike* science tool and an unfolding method. For the maximum likelihood analysis, the Galactic diffuse emission was modeled using GALPROP [26], updated to include recent HI and CO surveys, more accurate decomposition into Galactocentric rings, and many other improvements, including analysis of the LAT data [23]. Also the residual background has been modeled and fitted with a simple power law. Concerning CRAB and Geminga pulsars, they have been modeled with proper broken power law. The second method unfolds the spectrum starting from the background evaluation and then reconstructs the flux using the covariance matrix of the instrument. The background is evaluated with the *gtmodel* Science Tool which creates a photon map of all diffuse components and point-like sources included in the region of interest. These maps, created for different energy bins, are supplied with the unfolding algorithm that reconstructs the flux in each energy bin [27], after the background subtraction. Both methods agree in giving an integral flux above 100 MeV of 5.6 $\pm 0.5 \times 10^{-7}$ photons $cm^{-2}\,s^{-1}\,MeV^{-1}$ and a shape which breaks a simple power law at few GeV with two spectral indexes which can be roughly estimated to be about 1.9 and 2.5, respectively.

Some diffusion estimation is needed in order to predict the steepening of the spectrum of IC443 as well as more data are necessary to have better indication about the energy break and the change of the indexes. The spectral shape is critical to distinguish among different models: in the paper by Zhang et al. [28] there is a prediction that the EGRET source and the TeV emission should be co-spatial, while in Torres et al. [29] a shifting of the source position as a function of the energy is expected. In other works [30–32] it was found that a cosmic ray origin of the radiation originated by the proton–proton interaction between cosmic-rays accelerated by the SNR and the molecular material in the medium, followed by pion decay is consistent with the 3EG J0617+2238. At this stage of analysis it is still too premature to permit any distinction among all published models.

3. Conclusions

A preliminary analysis of the observations of the IC443 vicinity with the Large Area Telescope onboard Fermi has been done with 6 months of data. The Fermi source detected in the vicinity of IC443 seems to be consistent in its overall features (flux and spectrum) with the earlier detected EGRET source 3EG J0617+2238. There is no evidence so far supporting the existence of HE emission from PWN CXOU J061705.3+222127 (neither pulsed nor steady). The analysis presented is still in a preliminary phase; a more complete one is in progress containing also the study of a possible source extension. With more data, after the first year of data taking, the extension will be claimed and more accurate spectral shape will be found.

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