Gamma-ray emission from the SNR IC 443 neighborhood

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***Abstract*. We present a report on the preliminary analysis of the observations of the IC 443 vicinity with the Large Area Telescope onboard Fermi. We study the localization and spectrum of the source found in the neighborhood of the supernova remnant (SNR), preliminarily assuming point-like emission.**

***Keywords*: gamma rays, supernova remnants (individual: IC 443)**

I. Introduction

IC 443 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 γ-ray sources (see Torres et. al. 2003 for a review).

Its multi-wavelength phenomenology has been studied since over the last several decades: IC 443 is an asymmetric shell-type SNR with a diameter of ∼45 arc minutes (e.g., Fesen & Kirshner 1980) and a medium age of about 3×10^4 yr (e.g., Lozinskaya 1981, Chevalier 1999, Bykov et al. 2008). Probably due to the interaction of the shock with molecular environments of different densities, two half shells appear in optical and radio images (e.g, Braun & Strom 1986, Leahy 2004, Lasker et al. 1990). IC 443 is included in Green's catalog (2004) with a spectral index of 0.36 and a flux density of 160 Jy at 1 GHz. It has been mapped with high angular resolution by VLA at 90 cm (Claussen et al. 1997) and at other frequencies (e.g., see Olbert et al. 2001 and references therein), and maser emission at 1720 MHz has been found in its neighborhood (e.g., Hewitt et al. 2006).

IC 443 is also bright in X-rays, and its vicinity has been observed with Rosat (Asaoka & Aschenbach 1994), ASCA (Keohane 1997), XMM (Bocchino & Bykov 2000, 2001, 2003, Bykov et al. 2005, Troja 2006), and Chandra (Olbert et al. 2001, Gaensler et al. 2006). Of these observations, complete coverage of the X-ray from IC 443 region was made with XMM (Bocchino & Bykov 2003), resulting in the detection of a 12 X-ray sources, all located in the relatively small region of SNR blast - molecular cloud interaction (bright in radio as well, see also Troja et al. 2006), a number much smaller than what would be expected for a younger SNR. The amount of molecular material nearby IC 443 seems plenty: Cornett et al. (1977) and De Noyer (1981) were among the first to present detailed observations of molecular lines followed by Dickman et al. (1992), Seta et al. (1998), and Torres et al. (2003). These works point to the existence, in the environment of IC 443, of a total mass of $\sim 1.1 \times 10^4$ M$_\odot$, 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 cm^{-3}) that is absorbing optical and X-ray radiation (e.g., Lasker 1990, Troja et al. 2006, a scenario already speculated by Cornett et al. 1977); with additional mass, estimated as 500-2000 M$_\odot$ (e.g., Dickman et al. 1992) being directly perturbed by the shock in the northern region of interaction, near the SNR itself and where the X-ray sources and radio emission are found.

Of special interest for our research are the previous detections of the IC 443 vicinity in high and VHE γ-rays. EGRET detected a γ-ray source above 100 MeV, co-spatial with the SNR, named 3EG J0617+2238 (Hartman et al. 1999), presenting a flux of (51.4±3.5) $\times 10^{-8}$ ph cm^{-2} s^{-1} and a photon spectral index of 2.01±0.06. An independent analysis of 1 GeV photons measured by EGRET resulted in the source GeV J0617+2237 (Lamb & Macomb 1997), also co-spatial with 3EG J0617+2238, at the center of the SNR. The MAGIC telescope discovered a VHE source, J0616+225 (Albert et al. 2007) which is displaced with respect to the position of the EGRET source, and co-spatial with what appears to be the most massive molecular cloud in the neighborhood, as measured by ^{13}CO and ^{12}CO emission maps. These results were simultaneously confirmed by observations with the VERITAS array (Humensky et al. 2008). A simple power law was fitted to the measured spectral points at VHE: $(1.0 \pm 0.2) \times 10^{-11}\,(E/0.4\mathrm{TeV})^{-3.1\pm0.3}\,\mathrm{cm^{-2}s^{-1}TeV^{-1}}$, with quoted errors being statistical and systematic errors estimated to be 35% in flux and 0.2 in spectral index. Finally, 3EG J0617+2238, GeV J0617+2237, and MAGIC J0616+225 positions, and their corresponding uncertainties, are all inconsistent with that of the pulsar wind nebula (PWN) CXOU J061705.3+222127 (Olbert et al. 2001, Bocchino & Bykov 2001).

In this context, we present here a preliminary analysis of the observations of the IC 443 vicinity with the Large Area Telescope onboard Fermi (LAT, see Atwood et al. 2009 for details). The Fermi observatory was launched on June 11, 2008 from Cape Canaveral, Florida. The LAT is an electron-positron pair production telescope featuring solid state silicon trackers sensitive to photons from ~ 20 MeV to ~ 300 GeV. It has a large ~ 2.4 sr field of view, and compared to earlier γ-ray missions, a large effective area (∼8000 cm^2 on axis), improved angular resolution (∼0.8 deg for 68% containment at 1 GeV) and small dead time (25 μs/event). The Fermi survey mode operations consists in a north and south rocking of the observatory, on alternate orbits, so that the entire sky is observed for 30 minutes every 3 hours. Thus, Fermi is ideally suited for long term all-sky observations. Data taking in survey mode began on August 4, 2008 at 15:43 UTC and has continued essentially uninterrupted to the end of the dataset used for this analysis, March 30, 2009.

II. Data analysis and results

The data was here analysed using the Fermi Science Tools package, assuming that the detection in the IC 443 vicinity is a point like source, the reality of which we defer for our full fledge publication. The standard onboard filtering, event reconstruction, and classification were applied to the data (Atwood et al. 2009), and for this analysis the high-quality events (diffuse class) are used. Times when the IC 443 region of interest was observed at zenith angle greater than 105^o were also excluded to avoid contamination of the Earth albedo photons.

With these cuts, a photon counts map of a 4^o region around the SNR is shown in Fig. 1. In this map, the contours of the earlier detected EGRET ($>$ 100 MeV) and MAGIC (TeV) sources are also shown, together with other multi-wavelength information (VLA contours). The best-fit position of the Fermi source is found with the *gtfindsrc* tool at RA=$06^{\rm h}17^{\rm m}16^{\rm s}.80$, DEC=$22^o$34'48" with a 95% CL error of 0.01^o for energies above 200 MeV (statistical error). This position is compatible with both, the position of the EGRET source 3EG J0617+2238 (Hartman et al. 1999) and that reported in the Fermi Bright Source List (Abdo et al. 2009) as 0FGL J0617.4+2234, which was already flagged as potentially associated with IC 443.

To study the energy spectrum of the Fermi detection, we used the standard maximum-likelihood spectral estimator *gtlike*, with Pass6 v3 instrument response function (IRFs). This tool fits a source model to the data. The energy spectrum of IC 443 was modeled together with galactic and extragalactic diffuse emission, and the nearby point sources found in the Bright Source List (Crab nebula and pulsar, and Geminga). The Galactic diffuse emission was modeled using GALPROP, described by Strong, Moskalenko, & Reimer (2004), and Strong (2007), updated to include recent HI and CO surveys, more accurate decomposition into Galactocentric rings, and many other improvements, including analysis of the LAT data (Abdo 2009b). The GALPROP run designation for our model is 54_45Xvarh7S. The Extragalactic component is modeled with a simple power law, as it is done for the Crab Nebula. The Crab and Geminga pulsars are more appropriately modelled with a power law with a super exponential cut off.

This preliminary spectrum analysis gives a flux for energies above 200MeV of $2{\cdot}10^{-7}$ ph/cm^2/s . A change in the spectral index is seen from -1.9 to -2.5 with a break around few GeV.

III. Conclusion

The Fermi source detected in the vicinity of IC 443 is consistent in its overall features (flux and spectrum) with the earlier detected EGRET source 3EG J0617+2238, but the higher quality of the LAT instrument is now able to distinguish several aspects that were before hidden. As a summary,

- With the data now at hand, and within the reach of this preliminary study, we find no evidence supporting the existence of HE emission from PWN CXOU J061705.3+222127, neither pulsed nor steady.
- Whereas the Fermi detection above 100 MeV is spectrally consistent with 3EG J0617+2238, we observe that there is a measurable change in the form of an steepening of the spectral slope with increasing energy.

The observational interest on IC 443 and its vicinity accounted for in the introduction was always accompanied by theoretical studies exploring this SNR as a possible HE emitter. Among the first such proposals, the work by Sturner & Dermer (1995), Esposito et al. (1996), and Gaisser et al. (1998) found that a cosmic-ray origin of the radiation (proton-proton interaction between cosmic-rays accelerated by the SNR and the molecular material in the medium, followed by pion decay) where consistent with 3EG J0617+2238. A change of slope within the Fermi range and the detection position with energy is predicted by Torres et al. (2008). We emphasize that this report is still preliminary and that a more complete one is being produced, containing also the analysis of the possible source extension. If such extension is proven to be significant, spectral and positions could be affected.

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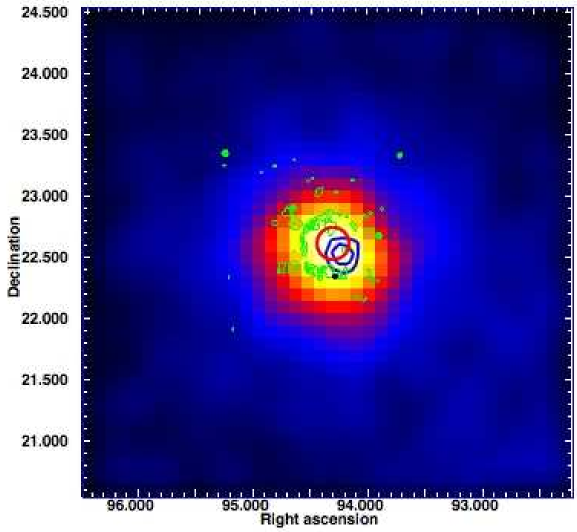

Fig. 1. Counts map around the IC443 location for energies above 200 MeV. VLA contours at 20 cm are shown in green, the EGRET position ($\sim$ 95 CL contour) and MAGIC contours from Albert et al. (2007) are shown in red and blue respectively. The small black point represent the position of CXOU J061705.3+222127.

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