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# Extended gamma-ray emission around the M31 galaxy: Fermi LAT observations

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Theories of galaxy formation predict the existence of extended gas halo around spiral galaxies. Simulations indicate that CRs escaping from the host galaxy could be retained in its vicinity for cosmological times. These CRs could interact with the tenuous hot halo gas and produce observable $\gamma$-rays. We have performed search for extended emission around the M31 galaxy – the closest large spiral galaxy. Our analysis of almost 7 years of the Fermi LAT data revealed the presence of a spatially extended emission excess around M31. The data can be fitted using the simplest morphology of a uniformly bright circle. The best fit gave a 4.7$\sigma$ significance for a 0.9° (12 kpc) halo with photon flux of $\sim (3.2 \pm 1.0) \times 10^{-9}$ cm$^{-2}$s$^{-1}$ and luminosity $(3.0 \pm 1.0) \times 10^{38}$ erg s$^{-1}$ in the energy range 0.3–100 GeV.

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## 1. Introduction

Theories of galaxy formation predict the existence of extended hot gas haloes around the spiral galaxies due to gas inflow from their neighbourghood [1, 2]. These coronae have been already observed in several galaxies by means of different methods [3, 4]. The existence of such a hot halo around the Milky Way is established rather robustly [5].

The Milky Way and other disk galaxies can also be surrounded by extended cosmic rays (CRs) haloes [6, 7]. CRs generated in the Milky Way escape dense regions of the Galaxy on time scales of 10-20 Myr, losing only minor part of their energy in interactions with the interstellar medium [8, 9]. These CRs, however, could be retained in the magnetized galactic halo for a considerable time if some magnetic fields of 10-100 nG strength exist there. The CRs would then interact with tenuous ($\sim 10^{-4}$ cm$^{-3}$) hot plasma producing gamma-rays, estimates show that the gamma-ray luminosity of this halo could be around $10^{39}$ erg s$^{-1}$ at energies above 100 MeV [7], the halo size could be of order of tens kpc.

It is difficult to disentangle observational manifestations of this halo from isotropic extragalactic background, but such haloes can be searched for around other disk galaxies. The most natural target is the halo around the nearby M31 (Andromeda) galaxy. With the expected angular size of several degrees and a gamma-ray luminosity of $\sim 10^{39}$ erg s$^{-1}$, such a halo could be detected by the Fermi LAT even from the Earth-M31 distance of $> 700$ kpc. The presence of a hot gas around M31, which is essential for the gamma-ray emission from the CR halo, was recently demonstrated by several different probes [10, 11, 12].

## 2. Data and data analysis

In our analysis we have used 83 months of Fermi LAT data collected since 2008 Aug 04 ( MET =239557417 s) until 2015 Jul 06 (MET=457860004 s). We have selected events that belong to the "SOURCE" class in order to have a sufficient number of events without losing in their quality. The PASS8_V2 reconstruction and v10r0p5[1] version of the Fermi science tools was used. As the expected signal is weak and diffuse, we have selected events with energies larger than 300 MeV, because of poorer angular resolution of the Fermi LAT at lower energies. Usual event quality cut: the zenith angle less than 100° (which is sufficient at these energies) has been used. See [13] for details of the analysis.

We took a circle of 10 degrees around the centre of the M31 galaxy ($\alpha_{J2000} = 10.6846°, \delta_{J2000} = 41.2692°$) as our region of interest (RoI). The data were analysed using the binned maximum likelihood approach [14] implemented in the *gtlike* utility, in which two model hypotheses were compared by their maximal likelihoods with respect to the observed photon distribution. The null hypothesis does not include the halo, the alternative hypothesis adds the halo to the list of sources of the null hypothesis.

The source model includes 26 sources from the 3FGL catalogue [15], the latest galactic interstellar emission model gll_iem_v06_rev1.fit, and the isotropic spectral template iso_source_v06.txt[2]. Parameters of these sources were allowed to change. We also included additional 69 point-like

[1] http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

[2] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html



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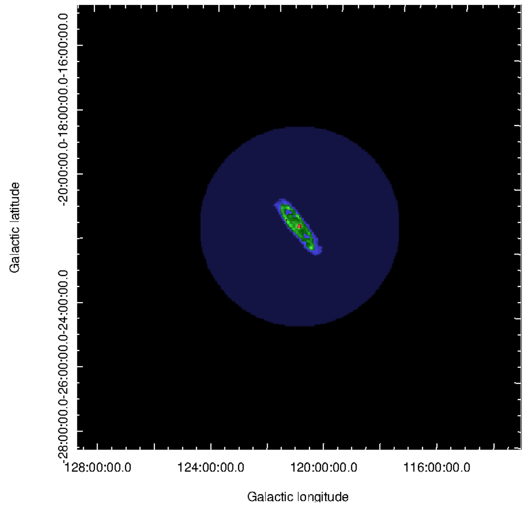


**Figure 1:** Templates of M31 and the halo with radius R=3.0°.

$\gamma$-ray emitters from the 3FGL catalogue between 10° and 15° from the RoI center with their parameters held fixed.

The M31 galaxy itself was modeled as an extended source based on the IR observations [16] (100$\mu$m normalized IRIS map) [17].

After that, halo spatial templates were inserted into the source model. The simplest spatial models – uniformly bright circles of different radii (from 0.1 to 4 degrees with 0.1 degree step) were used. Scarcity of the data on hand justifies this simple approach – a more sophisticated model would involve a larger number of parameters, thus diluting any obtained statistical significance.

The M31 galaxy and the CR halo were described by a simple power-law model:

$$dN/dE = N_0(E/E_0)^{-\Gamma} \tag{2.1}$$

The normalization $N_0$ and spectral index $\Gamma$ were allowed to vary during likelihood optimisation, while the energy scale $E_0$ was fixed at 1 GeV.

The evidence of the detection of $\gamma$-ray signal from the halo was evaluated in terms of the likelihood ratio test statistic:

$$TS = -2\ln\frac{L_{max,0}}{L_{max,1}} \tag{2.2}$$

where $L_{max,0}$ and $L_{max,1}$ are maximum likelihood values obtained when fitting the observed data using null and alternative hypothesis, respectively. If the *alternative* hypothesis is true, then $\sqrt{TS}$ is approximately equivalent to the source detection significance.

## 3. Results

The largest value $TS = 22$ was obtained for a halo with radius $R_{halo} = 0.9°$ (see Table **??**), which corresponds to a linear size of $\sim$ 12 kpc. The photon flux from the extended halo and luminosity in the energy range 0.3–100 GeV obtained from the fit are $\sim (3.2 \pm 1.0) \times 10^{-9}$ cm$^{-2}$s$^{-1}$

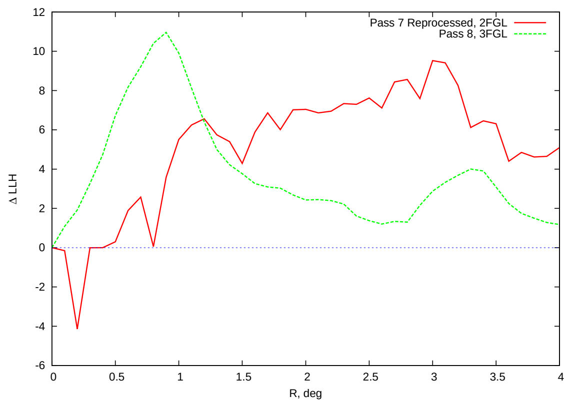


**Figure 2:** $\Delta LLH(R_{Halo})$ curves: older version (65 month of data, Pass7 Reprocessed events and 2FGL catalogue) is shown for comparison. The curve of $\Delta LLH(R_{Halo})$ is much smoother when the latest reconstruction is used. $TS \sim 2\Delta LLH$.

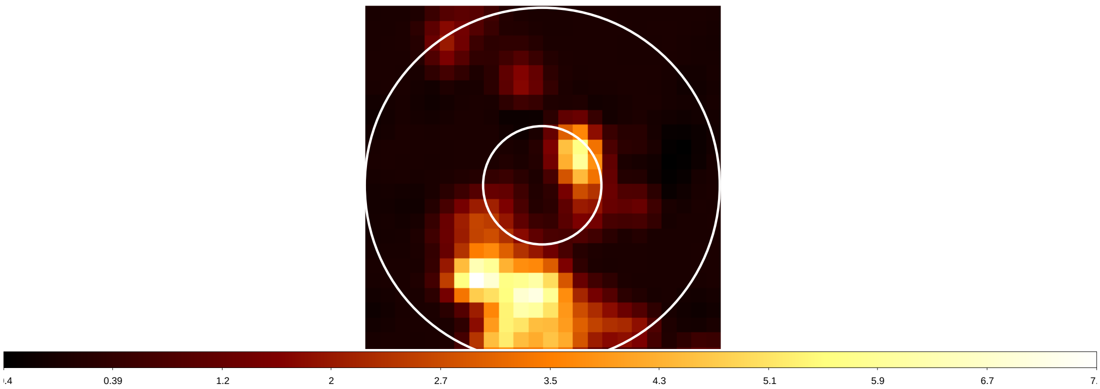


**Figure 3:** $TS$ map with the IRAS template for M31. A complex extended structure around the galaxy is clearly seen. 1- and 3- degree radius white circles are shown for convenience.

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and $(3.0\pm1.0)\times10^{38}$ erg s$^{-1}$ respectively. The spectral index is found to be rather soft: $\Gamma = 2.30\pm0.12$.

The extended template for the M31 galaxy fits the data considerably better than the simple point-like source ($TS_{ext} = 79$, $TS_{ps} = 67.3$), and the galaxy itself demonstrates quite soft spectrum: $\Gamma = 2.40\pm0.12$ with the photon flux $F = (2.6\pm0.4)\times10^{-9}$ph cm$^{-2}$ s$^{-1}$ in the 0.3-100 GeV energy range.

The results are presented in the fig. 3. There is large improvement of fit ($TS \sim 22$ ) when 0.9 degree radius halo is added. A marginal improvement ($TS \sim 8$ ) could be also achieved with an addition of 3 degree radius halo.

$\Delta LLH$ increase which corresponds to 0.9 degree halo could be caused by some unidentified source that had not been included into the 3FGL catalogue. We have calculated $TS$ map using the *gttsmap* utility (see fig. 3). There is some 'hotspot' at about 0.9 degree from the center of the galaxy ($l = 120.58°, b = -21.17°$) that could be due to FSRQ B3 0045+013. However, even after we included the source with these coordinates into our source model the $TS$ of the halo dropped only from 22 to 15, thus the whole increase could not be attributed to this only source. This excess could indicate a presence of compact CR halo of 10-15 kpc radius, like one we already indirectly observing in the Milky Way. Past activity of the M31 galaxy could have also formed the complex structure of the $TS$ excess at several degrees scale – see the example of the Fermi bubbles. More massive SMBH in the center of M31 could have injected much more energy in the form of cosmic rays in the circumgalactic space. Future observations would certainly clarify this issue.

## 4. Summary and conclusions

Using almost 7 years of the Fermi LAT data, we have performed searches for an extended $\gamma$-ray halo at energies larger than 300 MeV around the closest large spiral galaxy, M31. Such a gamma-ray halo could have appeared as a result of interactions of CRs flowing from the M31 galaxy with gas in its halo. We find that the Fermi LAT data suggest the presence of a spatially extended gamma-ray excess around M31. We tried to fit the data using the simplest morphology of a uniformly bright circle. The best fit gave $\sim 4.7\sigma$ significance for a $0.9^\circ$ radius (12 kpc) halo with the photon flux $\sim (3.2 \pm 1.0) \times 10^{-9}$ cm$^{-2}$s$^{-1}$ and luminosity $(3.0 \pm 1.0) \times 10^{38}$ erg s$^{-1}$ in the energy range 0.3–100 GeV. The presence of such a halo compellingly shows that considerable magnetic field (>100 nG) should extend around M31 up to at least 12 kpc distance.

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