Gamma-ray halo around the M31 galaxy as seen by the Fermi LAT

M. S. Pshirkov\textsuperscript{1,2,3*}, V. V. Vasiliev\textsuperscript{4†}, K.A.Postnov\textsuperscript{1*‡},
\textsuperscript{1}Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetsky prospekt 13, 119992, Moscow, Russia
\textsuperscript{2}Institute for Nuclear Research of the Russian Academy of Sciences, 117312, Moscow, Russia
\textsuperscript{3}Pushchino Radio Astronomy Observatory, 142290 Pushchino, Russia
\textsuperscript{4}IMPRS Max Planck Institute for Astronomy, D-69117, Heidelberg, Germany

ABSTRACT

Theories of galaxy formation predict the existence of extended gas halo around spiral galaxies. If there are 10-100 nG magnetic fields at several ten kpc distances from the galaxies, extended galactic cosmic ray (CR) haloes could also exist. Galactic CRs could interact with the tenuous hot halo gas to produce observable $\gamma$-rays. In this paper we have performed search for such a halo around the M31 galaxy – the closest large spiral galaxy. Our analysis of 5.5 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 $4.4\sigma$ significance for a $3^\circ$ (40 kpc) halo with photon flux of $\sim (1.9\pm1.1)\times10^{-9}$ cm$^{-2}$s$^{-1}$ and luminosity $(8.4 \pm 4.6) \times 10^{38}$ erg s$^{-1}$ in the energy range 0.3–100 GeV. The presence of such a halo compellingly shows that a 10-100 nG magnetic field should extend around M31 up to a 40 kpc distance.

Key words: gamma rays: galaxies, galaxies: individual:M31, ISM: magnetic fields, cosmic rays

1 INTRODUCTION

Theories of galaxy formation predict the existence of extended haloes around the spiral galaxies due to gas inflow from their neighbourhood (White & Reed 1993; Fukugita & Peebles 2000). This gas could be heated up to virial temperatures $10^6 - 10^7$ K when falling, therefore the galaxies should be surrounded by huge reservoirs of hot gas (coronae). There are several observational manifestations of these coronae: soft diffuse X-ray emission extending to several ten kpc from the central galaxy (Li et al. 2008), absorption in O VII line (Wang et al. 2005; Bregman & Lloyd-Davies 2007), distortions in the shape of gas clouds (Westmeier et al. 2005) and stripping of gas in the satellite galaxies by the ram-pressure of the halo gas (Blitz & Robishaw 2000), see (Putman et al. 2012) and references therein for an extensive review. The existence of such a hot halo around the Milky Way is established rather robustly by several different methods (Miller & Bregman 2013).

Extragalactic hot haloes are extremely elusive: they have been observed only in several normal galaxies without star-formation bursts (Bogdán et al. 2013). However, recently the implementation of stacking technique showed that there is a statistically significant excess in the extended X-ray signal from some normal late-type galaxies as well (Anderson et al. 2013), suggesting that even if the haloes are individually undetectable at the present level of sensitivity, they still could be discovered by analysis of groups of objects.

The Milky Way and other disk galaxies can also be immersed into extended cosmic rays (CRs) haloes. This idea was thoroughly investigated by Feldmann et al. 2013. It is well known that the Milky Way is not a perfect calorimeter for CRs: they rather quickly, on time scales of 10-20 Myr, escape dense regions of the Galaxy, losing only minor part of their energy in interactions with the interstellar medium (Strong et al. 2007, 2010). However, if strong enough magnetic fields exist far away from the central regions of the Galaxy, these CRs would not flow directly away to the intergalactic space, but would be instead retained in the magnetized galactic halo for a considerable time. Magnetic fields that are 10-100 times as weak as the galactic ones $O(\mu G)$ could be sufficient to contain these CRs for the cosmological time. Wandering CRs would interact with tenuous $(\sim 10^{-4}$ cm$^{-3}$) hot plasma producing gamma-rays via pionic channel. Estimates show that the gamma-ray luminosity of this halo could be around $10^{39}$ erg s$^{-1}$ at energies...
above 100 MeV (Feldmann et al. 2013). The size and shape of the halo cannot be firmly established and depend crucially on the propagation properties of CRs, the halo ‘half-light’ radius is estimated to be 20-40 kpc (Feldmann et al. 2013).

The contribution of the CR halo around our Galaxy to the isotropic gamma-ray background can be as high as 10%, and it is unclear how to disentangle it from the truly extragalactic component. However, such haloes can be searched for around other disk galaxies. The most natural target is the M31 galaxy (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 the discovery of certain absorption features in UV-spectrum of quasars projected close to the galaxy (Rao et al. 2013; Lehner et al. 2014) and distortions in the observed CMB spectrum in the vicinity of M31 due to interference of the halo gas (De Paolis et al. 2014).

The paper is organized as follows: in Section II we describe the data and method of data analysis, Section III contains our results, and summary and discussion are in Section IV.

2 DATA AND DATA ANALYSIS

In our analysis we have used 67 months of Fermi LAT data collected since 2008 Aug 04 (MET=239557417 s) until 2014 Mar 11 (MET=416196039 s). We have selected events that belong to the "SOURCE" class in order to have a decent number of events without compromising their quality. The latest reconstruction PASSSTREP\textsubscript{V15} and v9r33p4 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 at lower energies the Fermi LAT point spread function (PSF) quickly deteriorates. Usual event quality cuts, namely that the zenith angle should be less than 100°, have been imposed.

Smaller PSF allowed us to use smaller region of interest (RoI) as well – we took a circle of 10 degrees around the centre of the M31 galaxy ($\alpha_{2000}=10^h 68^m 46^s, \delta_{2000}=41.2692^\circ$). The data were analysed using the binned maximum likelihood approach (Mattox et al. 1994) implemented in the \textit{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 twelve sources from the 2FGL catalogue, the latest galactic interstellar emission model \texttt{ghi_em_v05.revl.fit}, and the isotropic spectral template \texttt{iso_source_v05.txt}. Parameters of these sources were allowed to change. We also included additional 15 point-like gamma-ray emitters from the 2FGL catalogue between 10° and 15° from the RoI center, and in the subsequent analysis their parameters were held fixed.

The M31 galaxy itself was modeled as an extended source based on the IR observations (Alivive-Deschenes & Lagache 2003) (100\(\mu\)m normalized IRIS map) following the prescriptions of the Fermi LAT collaboration (Abdo et al. 2010). The preliminary check of the source model quality – the map of the test statistics obtained with the \textit{gtismap} tool - revealed the presence of a bright source that was not included in the 2FGL catalogue. It turned out to be the 5C 3.178 blazar ($\alpha_{2000}=0^h 47^m 55^s.220, \delta_{2000}=+39^\circ 48’57”$) which went into a high state in November 2011 (Dickinson & Farnier 2013). We added this source to our source model.

Finally, extended halo spatial templates were inserted into the source model. We have used the simplest spatial models – uniformly bright circles of different radii (from 2 to 4 degrees with 0.5 degree step). Of course, it is not a realistic model, because some decrease in surface brightness towards the outer halo regions can be expected. On the other hand, scarcity of the data used justifies this simple approach – a more sophisticated model would inevitably involve a larger number of parameters, which would make fitting much harder and would dilute any obtained significance as well.

The M31 galaxy, the CR halo, and 5C 3.178 spectra were described by a simple power-law model:

$$dN/dE = N_0(E/E_0)^{-\Gamma}$$  \hspace{1cm} (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:

$$TS = -2 \ln \frac{L_{\text{max},0}}{L_{\text{max},1}}$$  \hspace{1cm} (2)

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

3 RESULTS

The highest value $TS = 19.8$ was obtained for a halo with radius $R_{\text{halo}} = 3^\circ$ (see Table 1), which corresponds to a linear size of ~40 kpc. The photon flux from the extended halo and luminosity in the energy range 0.3–100 GeV obtained from the fit are $\sim (1.9 \pm 1.1) \times 10^{-9}$ cm$^{-2}$s$^{-1}$ and $(8.4 \pm 4.6) \times 10^{38}$ erg s$^{-1}$ respectively. The spectral index is found to be rather hard: $\Gamma = 1.52 \pm 0.21$.

Two clusters of gamma-photons with energies larger than 1

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

2. http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

3. http://fermi.gsfc.nasa.gov/ssc/data/access/lat/

BackgroundModels.html

4. This is true for the case of a point-like source described by simple power-law model. The case of an extended source is much more cumbersome and this significance estimate should be treated only as an approximation.
Gamma-ray halo around the M31 galaxy

50 GeV spatially coinciding with the 3° halo were identified. The first photon cluster was produced by the blazar 1ES 0037+405 (1FHL J0040.3+4049). The second cluster consists of three photons and can be attributed to the source 1FHL J0053.9+4030 (Ackermann et al. 2013). The latter source has an extremely hard spectrum in 1FHL, $\Gamma = 1.15 \pm 0.50$, and should be briefly discussed.

Two out of three photons arrived in a 5-day interval (between $MET = 24144929.019161$ and $MET = 241822658.029170$), which could indicate a flaring activity in the source. Using the Simbad and NED databases we were able to find only the Seyfert 2 galaxy B3 0050+402B located at redshift $z = 0.15$ that could possibly be the counterpart of this hard-spectrum source. The gamma-ray flux at energies above 50 GeV is rather high: $F \simeq 3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ or even higher if the flare was real: $F \simeq 4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. At the redshift $z = 0.15$, this flux corresponds to a gamma-ray luminosity of $L \simeq 2.0 \times 10^{44}$ erg s$^{-1}$ ($L \simeq 2.5 \times 10^{49}$ erg s$^{-1}$). Note that these large high-energy gamma-ray luminosities and fast variability seem to be highly unusual for rather quiescent AGNs like Sy2, where no significant emission beaming can be expected.

Confusion with these two sources could lead to an artificial hardening of the CR halo spectrum. To test this, we have performed our model discarding all photons with energies exceeding 50 GeV. The resulting spectral index for the CR halo was found to be insignificantly softer — $\Gamma = 1.60 \pm 0.22$.

The extended template for the M31 galaxy fits the data considerably better than the simple point-like source ($T_{S,ext} = 72.4$, $T_{S,ps} = 57.7$), and the galaxy itself demonstrates quite soft spectrum: $\Gamma = 2.40 \pm 0.14$ with the photon flux $F = (2.9 \pm 0.5) \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$ in the 0.3-100 GeV energy range.

In order to exclude possible systematic and instrumental effects, which could affect our results, we have performed several tests.

(i) We have performed Monte Carlo simulations of the Fermi LAT observations using $gtobssim$ utility. We have simulated events in the energy range 0.3–100 GeV for the relevant time span (68 months) and the RoI described above. The model included the following components: the galactic and isotropic background, 27 point-like sources from the 2FGL catalogue, the point-like source 5C 3.178, the M31 galaxy (the IRAS 100μm template), and an extended halo with $R = 3.0^\circ$ characterized by the power-law spectral index $\Gamma = 1.9$ and photon flux $\text{flux}_{0.3-100\text{GeV}} = 2.0 \times 10^{-9}$ cm$^{-2}$s$^{-1}$. The parameters in the simulation are the same as in (i) above. After that the simulated files were subjected to our standard analysis. The source model for $gtlike$ included now an additional extended source — a halo with $R_{halo} = 3^\circ$. The resulting TS for the halo is found to be 17.1, the fitted power-law index is $\Gamma = 2.1 \pm 0.2$ and the fitted photon flux $\text{flux}_{0.3-100\text{GeV}} = (3.6 \pm 1.2) \times 10^{-9}$ cm$^{-2}$s$^{-1}$.

(ii) We have also performed the MC simulations like in (i) above adding the simulated halo photons and then trying to recover the halo parameters. The simulated set contains events in the energy range 0.3–100 GeV in our time span and RoI, from the following components: the galactic and isotropic background, 27 point-like sources from the 2FGL catalogue, the point-like source 5C 3.178, the M31 galaxy (the IRAS 100μm template), and an extended halo with $R = 3.0^\circ$ characterized by the power-law spectral index $\Gamma = 1.9$ and photon flux $\text{flux}_{0.3-100\text{GeV}} = 2.0 \times 10^{-9}$ cm$^{-2}$s$^{-1}$. The parameters in the simulation are the same as in (i) above. After that the simulated files were subjected to our standard analysis. The source model for $gtlike$ included now an additional extended source — a halo with $R_{halo} = 3^\circ$. The resulting TS for the halo is found to be 17.1, the fitted power-law index is $\Gamma = 2.1 \pm 0.2$ and the fitted photon flux $\text{flux}_{0.3-100\text{GeV}} = (3.6 \pm 1.2) \times 10^{-9}$ cm$^{-2}$s$^{-1}$.

(iii) We have created new TS map now including the 5C 3.178 source. There is $TS \sim 30$ excess at 2.5 degrees from the center of the M31 galaxy. The presence of an extraneous non-modeled source, if real, could result in erroneous fitting that could produce a significant TS even for a non-existent halo — the fitting procedure would ascribe some photons from the non-modeled source to the halo, thus artificially boosting its significance. However, a TS map with better resolution demonstrated drastic decrease of this suspicious TS down to a small value $TS \sim 8$ (Fig 3). This would be impossible if a real point-like source was present, when its TS would not depend on the binning size. Also, no plausible candidates were identified either in the Simbad or NED databases. Thus, we conclude that this TS excess could be produced by an inhomogeneity in the M31 halo. The possibility of this scenario is also confirmed by the inspection of the TS maps of the simulated haloes — they are far from being smooth and uniform, but rather consist of several random knots with $TS > 10$.

(iv) We have also checked that the smallness of our RoI does not considerably affect our analysis: we have performed the data analysis using an increased circle with 15° radius. The TS values from the halo remained essentially unchanged.

4 SUMMARY AND CONCLUSIONS

Using 5.5 years of the Fermi LAT data, we have performed searches for an extended γ-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 hard gamma-ray excess around M31. We tried to fit the data using the simplest morphology of a uniformly bright circle. The best fit gave
Figure 1. Templates of M31 and the halo with radius R=3.0°.

Figure 2. Top panel: TS map 10x10 degrees with 0.5x0.5 degree pixels, centered at the center of the M31 galaxy (α_2000 = 10.6846, δ_2000 = 41.2592). There is some visible excess with TS = 30 approximately at α_2000 = 12.476 δ_2000 = 42.55. Bottom panel: The zoomed TS excess region – 1x1 degree with 0.05x0.05 degree pixels. The brightest pixel now has only TS ~ 8.

Table 1. The results of the maximum likelihood binned analysis of the data in the energy range 0.3–100 GeV. N=1 is the model without halo (null hypothesis). N=2-6 are models with a halo (alternative hypothesis).

| N  | R_halo, ° | TSM31 | TSHalo | Δ ln(L) |
|----|---------|-------|--------|--------|
| 1  | –       | 72.4  | –      | –      |
| 2  | 2.0°    | 48.2  | 15.3   | 6.3    |
| 3  | 2.5°    | 54.0  | 16.3   | 7.3    |
| 4  | 3.0°    | 56.8  | 19.8   | 9.1    |
| 5  | 3.5°    | 62.5  | 13.0   | 6.0    |
| 6  | 4.0°    | 66.1  | 10.1   | 2.4    |

~ 4.4σ significance for a 3° radius (40 kpc) halo with the photon flux \( \sim (1.9 \pm 1.1) \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1} \) and luminosity \((8.4 \pm 4.6) \times 10^{38} \text{ erg s}^{-1}\) in the energy range 0.3–100 GeV. This luminosity is very close to \( \sim 1.0 \times 10^{39} \text{ erg s}^{-1}\) value theoretically predicted for the CR halo around the Milky Way due to p-p interaction of CRs with halo gas (Feldmann et al. 2013). The spectrum of the detected excess with the spectral index \( \Gamma = 1.6 \pm 0.2\) in the 300 MeV – 50 GeV energy range is also consistent with expected halo spectrum (see Fig.3 of Feldmann et al. 2013). The presence of such a halo compellingly shows that a 10-100 nG magnetic field should extend around M31 up to a 40 kpc distance. Independent observational checks of such a circum-galactic magnetic fields could be done, for example, by analysis of the Faraday Rotation Measures of background extragalactic sources (see, e.g., study by Pshirkov et al. (2011)). In addition, a synchrotron emission from secondary leptonic CR component could contribute at radio-frequencies \( \lesssim 100 \text{ MHz}\). Finally, gamma-ray signatures of dark matter particle annihilations (or decays) around M31 can be expected (Baltz 2008; Dugger et al. 2010). Further accumulation of data and improvements in the event reconstruction (Atwood 2013) and background modelling would allow us to check the existence of this halo with much better accuracy in the very near future.

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