Fermi-LAT Upper Limit for NGC 4151 and its Implications for Physics of Hot Accretion Flow

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We present preliminary results of our analysis of the Fermi-LAT data from the direction of NGC 4151. We find a new γ-ray source with a statistical significance σ > 5, shifted by 0.5° from the position of NGC 4151. Apparently, the source was bright only during a 1.5-year period between December 2011 and June 2013 and it strongly contaminated the signal from NGC 4151. Therefore, we neglect this period in our analysis. We find two additional, persistent γ-ray sources with high σ, shifted from NGC 4151 by ~1.5° and 5°, whose presence has been recently confirmed in the Third Fermi Catalog. After subtracting the above sources, we still see a weak residual, with σ ≳ 3, at the position of NGC 4151. We derive an upper limit (UL) for the γ-ray flux from NGC 4151 and we compare it with predictions of the ADAF model which can explain the X-ray observations of this object. We find that the Fermi UL strongly constrains non-thermal acceleration processes in hot flows as well as the values of some crucial parameters. Here we present the comparison with the hot flow models in which heating of electrons is dominated by Coulomb interactions with hot protons. In such a version of the model, the γ-ray UL, combined with the X-ray data, constrains the energy content in the non-thermal component of proton distribution to at most a few per cent, rules out a weak (sub-equipartition) magnetic field and favors a rapid rotation of the supermassive black hole.

1. INTRODUCTION

Low-luminosity AGNs, with the luminosities below \sim 0.01L_{Edd}, are likely to be powered by optically thin, hot accretion flows (a.k.a. ADAFs, see e.g. [12]). The two-temperature structure is a key property of ADAFs, as such flows are supported by the proton pressure. In their innermost parts, the hot protons have energies above the threshold for pion production. As estimated e.g. in [6,8], the decay of pions leads to substantial fluxes of γ-rays, which may be probed in nearby AGNs at the current sensitivity of Fermi-LAT surveys. The Fermi-LAT data for radio-quiet AGNs were analyzed in [10] (two years of data) and [2] (three years) and the derived upper limits are already quite stringent compared to expectation. In [11] we revisit the issue of searching the signatures of hadronic emission from hot flows and the related implications for hot-flow models. We perform the detailed analysis of nearby, low-luminosity Seyfert galaxies using over 6 years of Fermi-LAT data and we compare the results with the model predictions for a complete range of the model parameters. In this contribution we report our preliminary results for one of the best-studied AGNs, NGC 4151.

NGC 4151 is one the X-ray brightest AGNs, with the bolometric \sim 0.01L_{Edd}, showing no signatures of a relativistically distorted reflection component (constraints on the width of Fe Kα line imply the lack of an optically thick material within at least the innermost \sim 100R_⊙) as well as showing a spectral similarity to black hole binaries in their hard states (also most likely powered by hot flows), see e.g. [4]. All these properties make it a relevant objects for testing the hot flow scenario. Below we use the black hole mass \( M = 3.8 \times 10^7 M_⊙ \) from the stellar dynamical mass measurement [9].

2. LAT DATA ANALYSIS

We analyzed the data from the direction of NGC 4151, comprising 6.4 years of Fermi-LAT observations carried out between 2008 August 4 and 2015 January 10. Events we selected from a region with the radius of 10° centered on the position of NGC 4151. We performed the unbinned likelihood analysis using the v9r33p0 Fermi Science Tools with CALDB instrument response functions. We used the standard templates for the Galactic (gll_iem_v05.fits) and the isotropic (iso_source_v05.txt) backgrounds. In our initial model of the region we took into account only the sources from the Second Fermi Catalog (2FGL) [7], i.e. our model included the same sources as those used in [2]. 2FGL J1209.6+4121 (marked by the red circle in Fig. 1a) is the 2FGL source closest to NGC 4151, with the distance of \sim 2°.

Fig. 1a shows the TS map of the region, built after subtracting the 2FGL sources. The map reveals residual structures indicating the presence of additional point-like sources, marked by the green circles. For each of these objects we use the gtlike and gtfindsrc tools to find its significance, best-fit position and spectral parameters; the results are given in Table[3] Sources S1 (beyond the map in Fig. 1) and S3 have been recently reported in 3FGL [1], with parameters very similar to those estimated in our analysis. S2 is not reported in 3FGL, however, this source is
Table I New sources introduced in the model of the region around NGC 4151, not reported in 2FGL. (1) Source (see Fig. 1), (2) 3FGL name, (3) \texttt{gtlike} TS values, (4) and (5) \texttt{gtfindsrc} coordinates. Results for S2 were obtained using the data taken between December 2011 and June 2013; for the remaining sources the total data set for 6.4 years was used.

| (1) | (2) 3FGL name | (3) TS | (4) RA  | (5) DEC |
|-----|---------------|--------|---------|---------|
| S1  | 3FGL J1220.2+3434 | 191 | 185.06 | 34.57   |
| S2  | not reported   | 30    | 182.86 | 38.95   |
| S3  | 3FGL J1203.2+3847 | 32    | 180.81 | 38.79   |
| S4  | not reported   | 22    | 184.90 | 36.93   |

critical for the analysis of a signal from NGC 4151, as its distance of \( \sim 0.5^\circ \) is comparable (or smaller below \( \sim 1 \) GeV) to the LAT point spread function. Therefore, we check properties of this source in more details.

By using \texttt{gtsrcprob} we find that the position of S2 is determined mostly by 4 photons with energies between 10 and 20 GeV which arrived from the same direction (within 10 arcmin) between December 2011 and June 2013. At lower energies, neglecting the four events with \( E > 10 \) GeV, we also see the signature of increased activity of S2 during that period, in the form of an extended residual covering the nominal positions of NGC 4151 and S2.

In the TS map built for the data neglecting the above period (see Fig. 1b) we do not see a strong signal at the S2 position, we therefore conclude that S2 strongly dominated the emission from the region around NGC 4151 only during the 1.5 year out of the total 6.4 considered years. Note that S2 is not reported in 3FGL which includes sources detected with \( TS > 25 \) using the data taken during the four years up to 2012 July (i.e. covering only \( \sim 30\% \) of the time of the increased activity of S2).

For our further analysis we neglect the data taken during the 1.5 year when S2 was bright. We subtract the sources reported in 3FGL and we get the TS map shown Fig. 1b. The map shows a weak residual, which can be fully compensated for by adding the source at the nominal position of NGC 4151 and \texttt{gtlike} gives \( TS \simeq 8 \) for such a source. At its very low statistical significance, it is not possible to assess whether it represents a background fluctuation or an actual emission from the studied object; it may also contain some contribution from emission of S2 in its lower luminosity states.

We then derive the 95\% confidence level upper limit (UL) for the integrated photon flux from NGC 4151 neglecting the data between December 2011 and June 2013. The pion decay spectra can be approximated by a simple power-law only in limited energy ranges (see Fig. 2 below), therefore, we assume relevant values of the photon index, \( \Gamma \), and find the UL in the 0.3–1 GeV range to compare with the \( \pi^0 \)-decay spectra for the thermal distribution of protons, and in the 1–10 GeV to compare with the model assuming a power-law distribution of protons. The results are given in...
Here we focus on models with small $\delta$, i.e. with electrons heated by Coulomb interactions. We briefly summarize properties crucial for our final conclusions; Fig. 2 shows example spectra of radiation produced in a hot flow by thermal Comptonization and by $\pi^0$ decay.

(i) The nonthermal synchrotron radiation from $\pi^\pm$-decay electrons gives the dominating input of seed photons for Comptonization and it allows to reconcile the hot-flow model with the AGN X-ray data. It also provides an attractive explanation of spectral differences between AGNs and black-hole transients within the same physical model, see [5].

(ii) For bolometric $L \sim (0.001 - 0.01)L_{\text{Edd}}$, the size of the $\gamma$-ray photosphere (inside which the flow is opaque to $\gamma$-rays) equals several $R_g$. As a result, for models assuming thermal protons, the $\gamma$-ray flux detected by a distant observer is reduced by several orders of magnitude, because the $\gamma$-rays are produced mostly inside the photosphere. We note that [8] assessed comparable X-ray and $\gamma$-ray fluxes from flows surrounding rapidly rotating black holes. However, they neglected the GR transfer and $\gamma\gamma$ absorption; taking into account these effects we get, for thermal protons, the $\gamma$-ray fluxes smaller by several ($\sim 3$) orders of magnitude than the X-ray flux.

(iii) In models assuming a thermal distribution of protons, the $\gamma$-ray flux is extremely sensitive to the value of $\beta$. In flows with smaller $\beta$ (larger $B$), a larger fraction of the accretion power is used to build up the magnetic field strength; therefore, the energy heating the particles, and hence the proton temperature, is smaller. As for thermal protons the $\gamma$-ray luminosity, $L_\gamma$, is extremely sensitive to the proton temperature, the above effect leads to the difference by 2 – 3 orders of magnitude between $L_\gamma$ for a strong (in equipartition with gas) and weak magnetic field.

(iv) The proton temperature increases with $a$ and hence the $\gamma$-ray emissivities strongly depends on $a$ for thermal protons. However, the largest difference be-
Figure 3: The $\gamma$-ray (1–10 GeV) luminosity Eddington ratio as a function of the X-ray (2–10 keV) luminosity Eddington ratio. The squares and circles show the hot flow model predictions for the nonthermal proton distribution with $s = 2.1$. The Fermi UL was obtained for the assumed $\Gamma = 2.1$ in the 1–10 GeV range (see Table 2) and the average X-ray luminosity was estimated from the Swift-BAT data. The red circles are for $a = 0.998$, $\beta = 1$, $\dot{m} = 0.1$ and 0.3; the blue squares are for $a = 0.95$, $\beta = 9$, $\dot{m} = 0.3$ and 0.8.

Figure 4: The same as in Fig. 3 but the model points are for the thermal distribution of protons and the $\gamma$-ray Eddington ratio is determined for the 0.3–1 GeV range; $\Gamma = 4$ was assumed for the Fermi UL.

Between the emissivities occurs within the photosphere and, therefore, the dependence of the observed $L_\gamma$ on $a$ is reduced by $\gamma\gamma$ absorption. On the other hand, a sufficiently strong input of seed photons from the emission of $\pi^\pm$-decay electrons requires either a rapid rotation of the black hole or a significant content of nonthermal protons.

Using the publicly available Swift-BAT data [3] we find the average X-ray luminosity of NGC 4151 between 2009 and 2014 (we find that it corresponds to the intermediate state as defined in [4]), which then allows us to compare the $L_\gamma$ predicted by the model with the Fermi UL. The results are shown in Figs 3 and 4. For the power-law distribution of protons (Fig. 3) the UL is over an order of magnitude lower than the model prediction, which constrains the energy content in the nonthermal component of the proton distribution to at most a few per cent.

For the thermal distribution of protons (Fig. 4), the Fermi UL is sufficiently low to exclude models with large $\beta$, which, taking into account the above, rules out any version of the model with a weak magnetic field. For an equipartition value of $\beta \sim 1$ the predicted flux is below the UL value.

Then, the Fermi data favor a strongly magnetized plasma with a weak content of nonthermal protons. For such a case, a high spin value is required for a sufficiently strong flux of seed photons from nonthermal emission of pion-decay electrons.

4. SUMMARY

We thoroughly analyzed the $\gamma$-ray data from a region around NGC 4151, which led us to identification of new $\gamma$-ray sources. After subtracting their contribution, we get a weak residual signal at the position of NGC 4151. At its low statistical significance, $\sigma < 3$, it is not possible to assess its nature.

Comparison of the derived upper limits with the model predictions allows to constrain several crucial quantities which illustrates the potential of Fermi measurements in probing the properties of flows powering AGNs at low luminosities.

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