Discovery of $\gamma$-ray emission from the broad-line radio galaxy Pictor A

Anthony M. Brown* and Jenni Adams

Department of Physics and Astronomy, University of Canterbury, Christchurch 8140, New Zealand

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ABSTRACT

We report the discovery of high-energy $\gamma$-ray emission from the broad-line radio galaxy (BLRG) Pictor A with a significance of $\sim5.8\sigma$ [test statistic (TS) = 33.4], based on three years of observations with the Fermi Large Area Telescope (LAT) detector. The three-year-averaged $E > 0.2$ GeV $\gamma$-ray spectrum is adequately described by a power law, with a photon index, $\Gamma$, of $2.93 \pm 0.03$ and a resultant integrated flux of $F_\gamma = (5.8 \pm 0.7) \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$.

A temporal investigation of the observed $\gamma$-ray flux, which binned the flux into year-long intervals, reveals that the flux in the third year was 50 per cent higher than the three-year-averaged flux. This observation, coupled with the fact that this source was not detected in the first two years of Fermi-LAT observations, suggests variability on time-scales of a year or less.

Synchrotron self-Compton modelling of the spectral energy distribution of a prominent hotspot in Pictor A’s western radio lobe is performed. It is found that the models in which the $\gamma$-ray emission originates within the lobes predict an X-ray flux larger than that observed. Given that the X-ray emission in the radio lobe hotspots has been resolved with the current suite of X-ray detectors, we suggest that the $\gamma$-ray emission from Pictor A originates from within its jet, which is in agreement with other $\gamma$-ray-loud BLRGs. This suggestion is consistent with the evidence that the $\gamma$-ray flux is variable on time-scales of a year or less.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: Pictor A = PKS 0518–458 – galaxies: jets – gamma-rays: galaxies.

1 INTRODUCTION

The unified model of active galactic nuclei (AGN) attributes the bright nucleus at the centre of some galaxies to a supermassive black hole (SMBH)–accretion disc system surrounded by regions of broad-line and narrow-line gas clouds. Within this unified model, the difference between radio-loud (RL) and radio-quiet (RQ) AGN is explained by RL AGN possessing a relativistic jet emanating approximately perpendicular from the disc (Antonucci 1993; Urry & Padovani 1995).

The early success of the unified AGN model was its ability to explain the observational characteristics of the different RL AGN subclasses primarily by the size of the angle between the relativistic jet and the observer’s line of sight. However, while the unified model works well to first order, there is growing evidence that it is an oversimplification (e.g. Aharonian et al. 2007; Kharb, Lister & Cooper 2010) and there are still several key fundamental questions that remain to be answered.

One of these questions is why relativistic jets only appear to be present in 10–20 per cent of AGN. This question is often included in the broader issue of how accretion and ejecta are linked in AGN (e.g. Blandford & Znajek 1977; Blandford & Payne 1982; Sikora, Stawarz & Lasota 2007; McNamara, Rohanizadegan & Nulsen 2011). To address this issue, the accretion disc–relativistic jet connection needs to be studied across a wide variety of RL AGN types. Broad-line radio galaxies (BLRGs) appear to be vital in such a study. With the line of sight orientated at an intermediate angle relative to the relativistic jet, BLRGs exhibit both jet-related and disc-related photon emission processes. BLRGs therefore allow us to investigate how the processes of accretion (disc) and ejection (jet) relate to each other, and as such, represent a powerful diagnostic tool through which to understand this disc–jet connection.1

The successful launch of the Fermi $\gamma$-ray Space Telescope affords us an ideal opportunity to investigate the accretion disc–jet connection in AGN. The ability of the Fermi Large Area Telescope (LAT) detector to scan the entire $\gamma$-ray sky every three hours allows us to search for $\gamma$-ray emission from AGN unbiased by activity state or AGN subclass. Recently, the two-year LAT AGN catalogue has been released (2LAC), with the 2LAC clean sample

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1 It should be noted that while the $\gamma$-ray emission processes of radio galaxy jets are thought to be somewhat different from those of blazars, BLRGs still allow us to investigate how the global jet emission is related to the accretion disc processes (Georganopoulos & Kazanas 2003; Ghisellini, Tavecchio & Chiaberge 2005).
consisting of 885 sources (Abdo et al. 2011a). Of these sources, the vast majority are of the blazar subclass; however, there is a growing number of other AGN subclasses, including radio galaxies and narrow-line Seyfert 1 galaxies, detected as γ-ray sources (Abdo et al. 2009a,b,c,d,e; Kataoka et al. 2010; Brown & Adams 2011; Foschini 2011; Foschini et al. 2011). This increase in the number of different AGN subclasses detected as γ-ray sources is extremely important for the phenomenological studies required to investigate the connection between accretion and ejection.

To date, two BLRGs have been detected as γ-ray sources, 3C 120 and 3C 111 (Abdo et al. 2010b). To investigate the connection between accretion and ejection in BLRGs, Kataoka et al. (2011) were recently able to successfully model the broad-band spectral energy distribution (SED) of both 3C 111 and 3C 120 with a combined model incorporating accretion disc emission, taken from Koratkar & Blaes (1999), and relativistic jet emission, taken from Soldi et al. (2008). Kataoka et al. also applied this combined disc–jet model to the two-year data set of a sample of 18 X-ray bright BLRGs. While this study did not reveal any new γ-ray-emitting BLRGs, it did find that five of the BLRG sample have flux upper limits that were very close to the flux level predicted by the disc–jet model (Kataoka et al. 2011). Motivated by the proximity of the upper limits to the model prediction, we utilized a larger three-year Fermi data set to search for γ-ray emission from the most promising BLRG candidates. In total four BLRG sources were studied. While three of these did not show significant γ-ray emission, our analysis revealed that Pictor A is a high-energy γ-ray source.

Pictor A (z = 0.035; Liu & Zhang 2002; Eracleous & Halpern 2004) is an archetypical Fanaroff–Riley type II radio galaxy (FR II; Fanaroff & Riley 1974), with the total radio emission dominated by the jet-termination region observed as large radio lobes (e.g. Perley, Roeser & Meisenheimer 1997; Tingay et al. 2000). From optical spectra, Pictor A is defined as a BLRG (Danziger, Fosbury & Penston 1977). Interestingly Pictor A’s host galaxy has recently been found to possess a disc-like morphology (Inskip et al. 2010), indicating that Pictor A is hosted by a spiral galaxy, and thus is one of the rare examples against the AGN jet-elliptical host galaxy paradigm (see Foschini 2011 for more details). Due to its close proximity, Pictor A affords us an excellent opportunity to study not only the disc–jet connection but also the termination shock environment of the radio lobes. It is not surprising then that Pictor A has been extensively observed at many wavelengths.

Radio observations have found Pictor A to possess mildly relativistic jets containing subluminal moving components (Tingay et al. 2000). Very Long Baseline Array (VLBA) observations have also shown complex radio structure within Pictor A’s radio lobes in the form of compact hotspots (Tingay et al. 2008). These remarkable hotspots, along with the relativistic jet, have been studied with other observatories, including Spitzer, Hubble Space Telescope, XMN and Chandra (e.g. Thomson, Crane & Mackay 1995; Malkan, Gorjian & Tam 1998; Simkin et al. 1999; Wilson, Young & Shopbell 2001; Hardcastle & Croston 2005; Grandi, Malaguti & Fiocchi 2006; Migliori et al. 2007; Tingay et al. 2008). These observations have found structured magnetic fields within both the relativistic jet and radio lobe hotspots. Synchrotron self-Compton (SSC) modelling of these broad-band observations predicts the possibility of γ-ray emission through inverse Compton (IC) scattering of the synchrotron photons on the relativistic electrons. However, the predicted flux level is somewhat lower than the current γ-ray upper limits from both the Fermi and HESS collaborations (Aharonian et al. 2008; Zhang et al. 2009; Kataoka et al. 2011).

While Zhang et al. predicted γ-ray emission originating from the conditions in the radio lobe hotspots, the high-energy emission from BLRGs is often attributed to the relativistic jet viewed at intermediate angles (Grandi & Palumbo 2007; Sambruna et al. 2009). The question then arises as to whether the Pictor A γ-ray emission, which we have discovered, is associated with the radio lobe hotspots or with the relativistic jet. To address this question we perform SED modelling of a prominent hotspot in the western radio lobe of Pictor A using archival data at other photon energies. We take two approaches. In our first approach we tune the various parameters available in the SSC model so as to best fit the SED of the radio to optical data and the γ-ray data. We find that it is not possible to simultaneously fit these photon energy bands as well as the X-ray data with the X-ray flux overpredicted compared to observations. We then take the alternative approach of optimizing the fit of the radio to optical data and the X-ray data. We find a good fit to these data but the predicted flux at γ-ray energies is significantly below the flux that we have observed from Pictor A. This suggests that if the γ-ray emission is SSC in origin, it is not produced in the radio lobe hotspot region where the other wavelength photons are observed to originate.

The paper outline is as follows. In Section 2 we describe the Fermi-LAT observations and data analysis routines used in this study. Pictor A’s γ-ray characteristics are given in Section 3. In Section 4 we present our broad-band SED modelling using archival data at other photon energies, with the discussions on the SED modelling given in Section 5. The conclusions are given in Section 6. Throughout this paper, a Λ cold dark matter (ΛCDM) cosmology was adopted, with a Hubble constant of \( H_0 = 71 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_m = 0.27 \) and \( \Omega_\Lambda = 0.73 \) as derived from Wilkinson Microwave Anisotropy Probe results (Komatsu et al. 2009).

## 2 Fermi-LAT OBSERVATIONS AND DATA ANALYSIS

The LAT detector aboard Fermi, described in detail by Atwood et al. (2009), is a pair-conversion telescope, sensitive to a photon energy range from below 20 MeV to above 300 GeV. With a large field of view, \( \simeq 2.4 \text{ sr} \), improved angular resolution, \( \sim 0.8 \text{ at } 1 \text{ GeV} \), and large effective area, \( \sim 8000 \text{cm}^2 \) on axis at 10 GeV, Fermi-LAT provides an order-of-magnitude improvement in performance compared to its EGRET predecessor.

Since 2008 August 4, the vast majority of data taken by Fermi has been performed in all-sky-survey mode, whereby the Fermi-LAT detector points away from the Earth and rocks north and south of its orbital plane. This rocking motion, coupled with Fermi-LAT’s large effective area, allows Fermi to scan the entire γ-ray sky every two orbits, or approximately every three hours (Ritz 2007).

The data used in this analysis comprise all all-sky-survey observations taken during the first \( \sim 3 \) years of Fermi operation, between \( 4 \) Below 10 GeV photon energy, the 68 per cent containment angle of the photon direction is approximately given by \( \theta \sim 0.8/(E_\gamma/\text{GeV})^{0.8} \), with the 95 per cent containment angle being less than 1.6 times the angle for 68 per cent containment.

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\footnote{One of these five BLRGs was Pictor A, which hinted at γ-ray emission with a TS value of 20 from two years of observations.}

\footnote{Assuming a ΛCDM cosmology and \( H_0 = 71 \text{ km s}^{-1} \text{Mpc}^{-1} \) (Komatsu et al. 2009), Pictor A has a luminosity distance of about 148 Mpc. At this distance 1 arcsec corresponds to approximately 700 pc.}
3 $\gamma$-RAY CHARACTERISTICS

To investigate the $\gamma$-ray properties of Pictor A, we utilized the unbinned maximum-likelihood estimator of the Fermi-LAT Science Tools’ GTLIKE routine. GTLIKE allows us to fit the data with a series of both point and diffuse sources of $\gamma$-rays. The model used to calculate the likelihood of $\gamma$-ray emission from Pictor A was a combination of the most recent galactic and extragalactic diffuse models, as given in Section 2, and all point sources within an 8$\degree$ radius of interest (ROI) centred on Pictor A. Each point source was modelled with a power-law spectrum of the form $dN/dE = A \times E^{-\Gamma}$ with both parameters, photon index, $\Gamma$, and normalization, $A$, free to vary. The coordinates for each point source within the ROI were taken from the second Fermi-LAT Catalogue (2FGL; Abdo et al. 2011a). In addition, a 10$\degree$ radius sky map of the three-year data set was used to search for any other sources in the ROI that were not present in the 2FGL.

As a further check, the spatial distribution of the test statistic$^5$ values obtained from the GTLIKE fit was also utilized to identify any other possible sources in the ROI that were not present in the 2FGL. The TS distribution indicated the presence of two TS peaks within $1\degree$ of Pictor A. One of these peaks has a TS value of 76.6 and is spatially coincident with the blazar BZQ J0515−4556. Indeed, BZQ J0515−4556 is present in the 2FGL and therefore was already included in the model file.

The other TS peak is separated from Pictor A by $\sim 0.9\degree$, located at the position $(\alpha_{2000}, \delta_{2000}) = (81.3, -45.9)$. With a TS value of 13.8, or $\sim 3.7\sigma$, this TS peak suggests the presence of another $\gamma$-ray source which is not in either the 1FGL or 2FGL catalogues. However, given that the TS value is below the detection threshold of 25, this emission is not yet significant enough to be formally classified as a $\gamma$-ray source.

Another Fermi-LAT Science Tool, GTFINDSRC, was applied to the 8$\degree$ ROI around Pictor A to localize the origin of the $\gamma$-ray emission. Using the same combined diffuse and point-source model that was applied during the GTLIKE routine, the $\gamma$-ray emission that is associated with Pictor A is located at $(\alpha_{2000}, \delta_{2000}) = (80.17, -45.61)$, with a 95 per cent error radius of 0.08. The GTFINDSRC routine was also able to identify and localize the emission from both BZQ J0515−4556 and the other TS ‘hotspot’ as two $\gamma$-ray sources separate from Pictor A.

Once satisfied that all point sources within an 8$\degree$ ROI have been accounted for, we applied GTLIKE to the three-year data set. With the combined diffuse and 8$\degree$ ROI point-source model, we obtain the following best-fitting power-law function for Pictor A:

$$dN/dE = (4.23 \pm 0.44) \times 10^{-10} \left(\frac{E}{100 \text{ MeV}}\right)^{-2.93 \pm 0.03} \text{ photons cm}^{-2} \text{s}^{-1} \text{MeV}^{-1},$$

which equates to an integrated flux, in the 0.2 < $E_\gamma$ < 300 GeV energy range, of

$$F_{E>0.2 \text{ GeV}} = (5.8 \pm 0.7) \times 10^{-9} \text{ photons cm}^{-2} \text{s}^{-1},$$

only taking statistical errors into account. Primarily governed by the uncertainty in the effective area, the systematic uncertainty of the integrated flux is energy dependent and is currently estimated as 10 per cent at 100 MeV, down to 5 per cent at 560 MeV and back to 10 per cent at 10 GeV photons (Abdo et al. 2011b).

From the power-law fit, the predicted $\gamma$-ray count was 337, with a test statistic of TS = 33.4, corresponding to a $\sim 5.8\sigma$ detection. Compared to other $\gamma$-ray BLRGs, 3C 120 and 3C 111, Pictor A’s $\gamma$-ray flux is a factor of 6 lower, and the spectral index is comparable, with a spectral index of $\sim -2.93 \pm 0.03$ for Pictor A compared to $-3.0 \pm 0.3$ for 3C 120 and $-2.7 \pm 0.2$ for 3C 111. On the other hand, the $\gamma$-ray luminosity for Pictor A is comparable to both 3C 120 and 3C 111, log($L_\gamma$) = 43.1 erg s$^{-1}$ compared to 43.6 and 43.9 erg s$^{-1}$, respectively (Kataoka et al. 2011).

To investigate the possibility of temporal variability in Pictor A’s $\gamma$-ray flux, the three-year data set was binned into one-year periods and analysed separately with GTLIKE. As with the spectral analysis, only 0.2 < $E_\gamma$ < 300 GeV events were considered, with the appropriate quality cuts applied, and the same combined diffuse and 8$\degree$ ROI point-source model was used. Only the fluxes of temporal bins with TS > 10 ($\sim 3\sigma$) were plotted, with the 95 per cent confidence upper limit being calculated for the remaining temporal bin. The resultant light curve can be seen in Fig. 1, with the bold horizontal line indicating the three-year-averaged 0.2 < $E_\gamma$ < 300 GeV flux level.

A closer inspection of the individual photon energies reveals that the highest photon energy detected from Pictor A during this three-year data set has an energy of 109.8 GeV. Additionally, photons with energies of 99.7 and 91.3 GeV were also detected, both within 0.8$\degree$ of Pictor A. The spatial distribution of these highest energy photon events was compared to the sky map to confirm that none was spatially coincident with either BZQ J0515−4556 or the 13.8 TS peak. Taking the approach outlined in Neronov, Semikoz & Vovk (2010), the chance probability of the second highest photon being clustered within $1\degree$ of the highest photon is $\approx 0.107$. That is to say, the chance probability that these two photon events are not clustered background events is $\approx 89.3$ per cent. This value is $\sim 2\sigma$ and therefore the observed ‘clustering’ of $\gtrsim 90$ GeV photons around Pictor A is not statistically significant. It is worth noting that a GTLIKE likelihood analysis for all very high energy (VHE) $\gamma$-ray events, 90 < $E_\gamma$ < 300 GeV, from Pictor A, utilizing the same combined diffuse and 8$\degree$ ROI point-source model, finds a comparable statistical significance to Pictor A being a VHE $\gamma$-ray source, with a TS value of 4.99 or $\sim 2.2\sigma$. 

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$^5$ ‘Source’ class events equates to EVENT_CLASS = 2 in the PASS 7 data set. Source class events optimize the $\gamma$-ray detection efficiency as a function of residual charged-particle contamination and is best suited for localized sources as opposed to transient or diffuse sources.

$^6$ The test statistic, TS, is defined as twice the difference between the log-likelihood of two different models, $[\log(L_2 - \log L_1)]$, where $L_2$ and $L_1$ are defined as the likelihood when the source is included or not, respectively (Mattox et al. 1996).
These observations have discovered several bright \( \gamma \)-ray sources, including Pictor A, which was observed with the Fermi Gamma-ray Space Telescope and an electron energy density of \( \gamma = 10^7 \) eV, with broken power-law indices of \( \gamma > E \). The SSC modelling of the SED of Pictor A’s WHS from radio to \( \gamma \)-ray energies, it overpredicts the X-ray flux, both the magnetic field strength and electron population’s energy distribution were varied, optimizing the fit for the synchrotron radiation distribution, whilst accurately modelling the X-ray observations. The best fit for the X-ray data was described by an electron distribution of \( n_1 \), moving with Doppler factor \( \delta \) and filled with a random magnetic field of strength \( B \) and an electron population described by a broken power law (for more details, see Krawczynski et al. 2004). The radius of the emission region was fixed to the physical size of the WHS, \( R = 209 \) pc, as observed with the Hubble Space Telescope (Thomson et al. 1995) and the Doppler factor, \( \delta \), was fixed to 1 thus removing any Doppler boosting effects.

In our first approach, the SSC fit to the WHS SED, shown in Fig. 2, was originally optimized to account for the synchrotron radiation distribution, whilst accurately modelling our Fermi-LAT observations. The WHS SED was found to be best described by an electron distribution of \( E_{\text{min}} = 10^6 \) eV, \( E_{\text{break}} = 4 \times 10^{11} \) eV and \( E_{\text{max}} = 10^{13} \) eV, with broken power-law indices of \( n_1 = 2.4 \) and \( n_2 = 4.4 \) below and above the break energy, respectively. To reproduce the relative synchrotron and IC peak flux levels, a magnetic field of \( 4 \times 10^{-5} \) G and an electron energy density of \( 2.5 \times 10^{-6} \) erg cm\(^{-3} \) were required. The resultant SSC fit can be seen in Fig. 2 with the solid line representing the synchrotron spectrum and the dashed line representing the IC spectrum.

As can be seen in Fig. 2, while the best-fitting SSC model adequately describes the radio–optical and Fermi fluxes, it overpredicts the IC flux at X-ray energies by an order of magnitude. It is worth noting at this point that while smaller, this discrepancy is also present if the entire western radio lobe’s X-ray flux is included in the SED (Migliori et al. 2007).

To address the overprediction of the X-ray flux, both the magnetic field strength and electron population’s energy distribution were varied, optimizing the fit for the synchrotron radiation distribution, whilst accurately modelling the X-ray observations. The best fit for the X-ray data was described by an electron distribution of \( n_1 \), moving with Doppler factor \( \delta \) and filled with a random magnetic field of strength \( B \) and an electron population described by a broken power law (for more details, see Krawczynski et al. 2004). The radius of the emission region was fixed to the physical size of the WHS, \( R = 209 \) pc, as observed with the Hubble Space Telescope (Thomson et al. 1995) and the Doppler factor, \( \delta \), was fixed to 1 thus removing any Doppler boosting effects.

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\(E_{\text{min}} = 10^6\,\text{eV}, E_{\text{break}} = 2 \times 10^{11}\,\text{eV}\) and \(E_{\text{max}} = 4 \times 10^{13}\,\text{eV}\), with broken power-law indices of \(n_1 = 2.4\) and \(n_2 = 4.4\), a magnetic field of \(1.5 \times 10^{-4}\,\text{G}\) and an electron energy density of \(2.5 \times 10^{-7}\,\text{erg cm}^{-3}\). It should be noted that a slight change in the break and maximum energies of the electron population was required so as to not overpredict the flux of the high-energy synchrotron emission. The resultant ‘X-ray’ fit can be seen in Fig. 3. The fit parameters for Figs 2 and 3 are shown in Table 1, along with the fit parameters for Zhang et al.’s modelling of Pictor A’s WHS and the Fermi-LAT Collaboration’s modelling of Cen A’s core and radio lobes.

5 DISCUSSION

In both Figs 2 and 3, the radio to optical emission can be seen to be accurately described by the process of synchrotron radiation. It is not, however, possible to simultaneously describe the X-ray and \(\gamma\)-ray fluxes by the IC component of the one-zone SSC model. Therefore, our SED modelling provides support for the synchrotron origin of the low-energy emission of the WHS of Pictor A. However, assuming that the SSC model is the dominant mechanism for the observed X-ray flux from the WHS, our SED modelling suggests that Pictor A’s observed \(\gamma\)-ray emission is either produced through processes other than SSC, or that the \(\gamma\)-ray originates from either Pictor A’s relativistic jet or central core region.

Other possible mechanisms through which the \(\gamma\)-rays can be emitted include the external Compton (EC) model or hadronic models involving photon–proton or proton–proton interactions. Similar to the SSC model, the EC model simply has an external photon field, such as the cosmic microwave background (CMB), as the dominant photon field on which the IC process acts. It is worth noting that Migliori et al. attributed the X-ray emission from the WHS to the EC of the CMB (Migliori et al. 2007); however, more recently Zhang et al. found the EC contribution from the CMB to be negligible (Zhang et al. 2009). While we have not considered EC during our SED modelling of Pictor A’s WHS, doing so would simply allow us to relax the energetic requirements of the electron population in the hotspot.

![Figure 3. SSC modelling of the SED of Pictor A’s WHS from radio to \(\gamma\)-ray, plotted as \(vF_v\). The optical data are taken from Meisenheimer et al. (1997), the radio and infrared data are taken from Tingay et al. (2008), the X-ray data are taken from Migliori et al. (2007), the VHE \(\gamma\)-ray upper limit, marked by an arrow, is taken from Aharonian et al. (2008) and the Fermi data point is reported here. The solid line is the synchrotron spectrum and the dashed line is the inverse Compton spectrum. The SSC fit has been optimized to describe the radio to X-ray flux.](attachment:image.png)

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In-depth hadronic interpretation of the Fermi-LAT observations is outside the scope of this paper. Nonetheless, we do note that neutrino telescopes, such as ANTARES and IceCube, have the potential to constrain the hadronic contribution to Pictor A’s observed \(\gamma\)-ray flux (e.g. Becker et al. 2007; Abbasi et al. 2011; Adrian-Martínez et al. 2011; Abbasi et al. 2012).

However, it seems more likely that the reason why our SED modelling was unable to marry the WHS observations with the observed \(\gamma\)-ray flux is that the \(\gamma\)-ray emission is of jet origin. As mentioned in Section 1, \(\gamma\)-ray emission from BLRGs is traditionally interpreted as originating from a relativistic jet viewed at intermediate angles from the line of sight (e.g. Grandi & Palumbo 2007; Sambruna et al. 2009; Kataoka et al. 2011). Flux variability is a fundamental property of astrophysical jets. Indeed, evidence for variability in Pictor A’s jet has been observed with Chandra which has observed the X-ray flux from Pictor A’s western jet to vary on time-scales of years (Marshall et al. 2010). Evidence for variability in Pictor A’s \(\gamma\)-ray flux can be seen in Fig. 1, which hints at \(\gamma\)-ray flux variability on time-scales of a year or less. This evidence is primarily seen in the third year of observations, with a \(\sim 4\sigma\) detection of Pictor A and a flux level that is 50 per cent larger than the three-year average. Taking statistical errors into consideration, the difference between the third-year and three-year-averaged flux levels is significant at the \(\sim 4\sigma\) level. However, this is just short of the \(5\sigma\) level, and as such, further Fermi-LAT observations are needed to confirm this observational characteristic.

At this point, we briefly turn our attention to other possible locations for the \(\gamma\)-ray emission, namely the core region of Pictor A within the immediate vicinity of the SMBH. Magnetospheric emission models of AGN core regions have been successfully invoked to explain the \(\gamma\)-ray emission from other radio galaxies such as M87 (e.g. Rieger & Aharonian 2008). However, as highlighted in Brown & Adams (2011), for these models \(L_{\text{IC}} \propto M_{\text{BH}}\) is expected, where \(L_{\text{IC}}\) is the IC luminosity, which in this case is the \(\gamma\)-ray luminosity, and \(M_{\text{BH}}\) is the SMBH mass. Given that Pictor A’s SMBH mass is an order of magnitude larger than Cen A’s, whilst the \(\gamma\)-ray flux is two orders of magnitude smaller, we find it unlikely that a magnetospheric emission model significantly contributes to the observed \(\gamma\)-ray emission and suggests that the observed \(\gamma\)-ray emission from Pictor A is indeed of jet origin.

Therefore, given that Chandra has resolved X-ray emission from the WHS, the SSC fit of Fig. 3 indicates that the observed \(\gamma\)-ray flux cannot be attributed to an SSC process within the hotspots of Pictor A’s radio lobes. This conclusion, coupled with the evidence of variability observed in Fig. 1, suggests that the \(\gamma\)-ray emission from Pictor A originates from within its jet, in agreement with the SED modelling of other \(\gamma\)-ray-loud BLRGS.

6 CONCLUSIONS

We have reported the discovery of Pictor A as a \(\gamma\)-ray source with a significance of 5.8\(\sigma\), utilizing the first three years of observations with the Fermi-LAT detector. These observations have found the \(E > 0.2\,\text{GeV}\) spectrum to be well described by a power law with \(\Gamma = -2.93 \pm 0.03\), which is comparable to the other Fermi-LAT-detected BLRGS, 3C 120 and 3C 111.

\[8\] It is also worth noting that the flux in the third year is approximately 30 per cent larger than the 95 per cent flux upper limit set in the first year of observations. Furthermore, the \(3\sigma\) flux in the second year is over five times smaller than the flux observed in the third year of observations.
Table 1. Summary of fit parameters. The Cen A core fit parameters are taken from Abdo et al. (2010a), while the Cen A radio lobe fit parameters are taken from Abdo et al. (2010c). It should be noted that the Cen A radio lobe fit considers four separate emission regions, two for each radio lobe; we quote the fit parameters for the total northern lobe, since the particle energetics for the two emission regions in the north lobe are the same. The Zhang et al. Pic A fit parameters are taken from the SSC fit parameters in Zhang et al. (2009). The energy limits of the electron population ($E_{\text{min}}$, $E_{\text{break}}$ and $E_{\text{max}}$) from our fits have been converted to Lorentz factors ($\gamma_{\text{min}}$, $\gamma_{\text{break}}$ and $\gamma_{\text{max}}$) for comparison to the Cen A fits.

| Pic A (X-ray fit) | Pic A (Fermi fit) | Pic A (Zhang et al.) | Cen A core | Cen A lobe |
|------------------|------------------|-----------------------|-----------|-----------|
| Magnetic field (G) | $1.5 \times 10^{-4}$ | $4 \times 10^{-5}$ | $4.4 \times 10^{-5}$ | 6.2 | $8.9 \times 10^{-4}$ |
| Doppler factor ($\delta$) | 1 | 1 | 1 | 1 | 1 |
| Volume (pc$^3$) | $2.14 \times 10^{-7}$ | $2.45 \times 10^{-8}$ | $4.1 \times 10^{-7}$ | $3.8 \times 10^{-9}$ | $3.6 \times 10^{15}$ |
| $\Gamma_1$ | 2.4 | 2.4 | 2.38 | 1.8 | 2.1 |
| $\Gamma_2$ | 4.4 | 4.4 | 3.9 | 4.3 | 3.0 |
| $\gamma_{\text{break}}$ | 196 | 196 | – | 300 | 1 |
| $\gamma_{\text{max}}$ | $7.8 \times 10^5$ | $3.9 \times 10^5$ | – | $3.6 \times 10^6$ |
| $\gamma_{\text{break}}$ | $2 \times 10^7$ | $7.8 \times 10^7$ | – | $1 \times 10^8$ | $3.3 \times 10^5$ |

Pictor A’s three-year-averaged $0.2 < E_{\gamma} < 300$ GeV flux is $(5.8\pm0.7) \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$, which equates to a $\gamma$-ray luminosity of $\log(L_{\gamma}) = 43.1$ erg s$^{-1}$. Pictor A’s $\gamma$-ray flux was thus found to be approximately six times smaller than that of 3C 120 and 3C 111, but due to its close proximity, Pictor A’s luminosity is comparable with other $\gamma$-ray-loud BLRGs.

Pictor A’s year-binned light curve suggested variability in the $\gamma$-ray flux, with the third-year flux level being 50 per cent larger than the three-year average. However, further observations are needed to confirm this observational property.

SSC modelling of the WHS SED found that it was only possible to account for the $\gamma$-ray emission with an SSC model at the expense of greatly overpredicting the flux at X-ray energies. Given that the X-ray emission in the WHS has been resolved with the current suite of X-ray detectors, we suggest that the $\gamma$-ray emission from Pictor A originates from within its jet, in agreement with other BLRGs detected with Fermi. This suggestion agrees well with the evidence that the $\gamma$-ray flux is variable on time-scales of a year or less.

The highest energy photon detected during this 3-year period was 109.8 GeV, with several $>90$ GeV photons also being observed. A likelihood analysis of the $90 < E_{\gamma} < 300$ GeV $\gamma$-ray events does not find any significant VHE emission. While the clustering of the highest energy events does not appear to be significant, it raises the interesting possibility of VHE $\gamma$-ray emission from Pictor A.

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