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FERMI LARGE AREA TELESCOPE GAMMA-RAY DETECTION OF THE RADIO GALAXY M87

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ABSTRACT

We report the *Fermi* Large Area Telescope (LAT) discovery of high-energy (MeV/GeV) γ-ray emission positionally consistent with the center of the radio galaxy M87, at a source significance of over 10σ in 10 months of all-sky survey data. Following the detections of Cen A and Per A, this makes M87 the third radio galaxy seen with the LAT. The faint point-like γ-ray source has a >100 MeV flux of 2.45 ($\pm$0.63) $\times$ 10^{-8} photons cm^{-2} s^{-1} (photon index = 2.26 $\pm$ 0.13) with no significant variability detected within the LAT observation. This flux is comparable with the previous EGRET upper limit (<2.18 $\times$ 10^{-8} photons cm^{-2} s^{-1}, 2σ), thus there is no evidence for a significant MeV/GeV flare on decade timescales. Contemporaneous *Chandra* and Very Long Baseline Array data indicate low activity in the unresolved X-ray and radio core relative to previous observations, suggesting M87 is in a quiescent overall level over the first year of *Fermi*-LAT observations. The LAT γ-ray spectrum is modeled as synchrotron self-Compton (SSC) emission from the electron population producing the radio-to-X-ray emission in the core. The resultant SSC spectrum extrapolates smoothly from the LAT band to the historical-minimum TeV emission. Alternative models for the core and possible contributions from the kiloparsec-scale jet in M87 are considered, and cannot be excluded.

Key words: galaxies: active – galaxies: individual (M87) – galaxies: jets – gamma rays: observations – radiation mechanisms: non-thermal

1. INTRODUCTION

As one of the nearest radio galaxies to us (D = 16 Mpc is adopted; Tonry 1991), M87 is amongst the best studied of its source class. It is perhaps best known for its exceptionally bright arcsecond-scale jet (Curtis 1918), well imaged at radio through X-ray frequencies at increasingly improved sensitivity and resolution over the decades (e.g., Biretta et al. 1991; Sparks et al. 1996; Marshall et al. 2002; Perlman & Wilson 2005). Near its central ∼(3–6) × 10^9 solar mass supermassive black hole (Macchetto et al. 1997; Gebhardt & Thomas 2009), the jet base has been imaged down to ∼0.01 pc resolution (∼15–30× the Schwarzschild radius; Junor et al. 1999; Ly et al. 2007; Acciari et al. 2009).

At the highest energies, M87 is regularly detected by HESS, MAGIC, and VERITAS with variable TeV emission on timescales of years and flaring in a few days (Aharonian et al. 2006; Albert et al. 2008; Acciari et al. 2008, 2009). The sensitivity of these Cherenkov telescopes has also enabled the detection of another well-known nearby radio galaxy Cen A (Aharonian et al. 2009). Without comparable imaging resolution to the lower energy studies, however, variability and spectral modeling are necessary to infer the production site of the TeV γ-rays and to deduce the source physical parameters.

At high-energy γ-rays (∼20 MeV–100 GeV), we are similarly poised for new radio galaxy discoveries with the Large Area Telescope (LAT) aboard the recently launched *Fermi Gamma-ray Space Telescope* (Atwood et al. 2009). Indeed, we report here the detection of a faint, point-like γ-ray source positionally coincident with M87 using the *Fermi*-LAT. After the confirmation of the EGRET discovery of Cen A (Sreekumar et al. 1999; Abdo et al. 2009c; A. A. Abdo et al. 2009, in preparation), and the recent detection of Per A/NGC 1275 (Abdo et al. 2009b), this is the third radio galaxy successfully detected by *Fermi*. Unlike the known variable TeV source, there is so far no evidence for variability of the MeV/GeV emission in M87. An origin of the LAT emission from the unresolved parsec scale jet (hereafter, denoted as the "nucleus" or "core") observed contemporaneously with *Chandra* and the Very Long Baseline Array (VLBA)[56] is discussed. Potential contributions from the larger-scale ($\gtrsim$0.1–1 kpc) jet to the unresolved γ-ray source are also briefly considered. Section 2 contains the details of the LAT observations, including a description of the *Chandra* and VLBA data utilized, with the discussion of these results in Section 3.

2. OBSERVATIONS

The *Fermi*-LAT is a pair creation telescope which covers the energy range from ∼20 MeV to >300 GeV (Atwood et al. 2009). It operates primarily in an "all-sky survey" mode, scanning the

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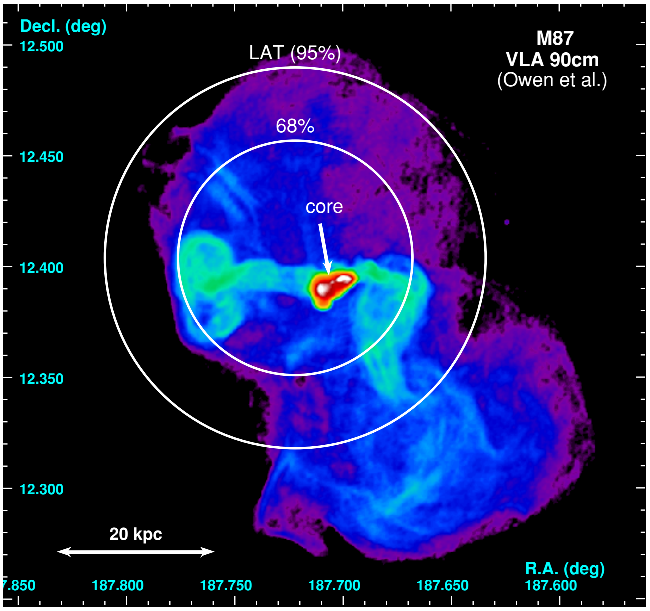

Figure 1. VLA $\lambda = 90$ cm radio image from Owen et al. (2000) with the LAT γ-ray localization error circles indicated: $r_{95\%} = 5'.2$ and $r_{68\%} = 3'.2$ (statistical only; see Section 2). The M87 core is the faint feature near the center of the few kpc-scale double-lobed radio structure (in white). At the adopted distance $D = 16$ Mpc, $1' = 4.7$ kpc.

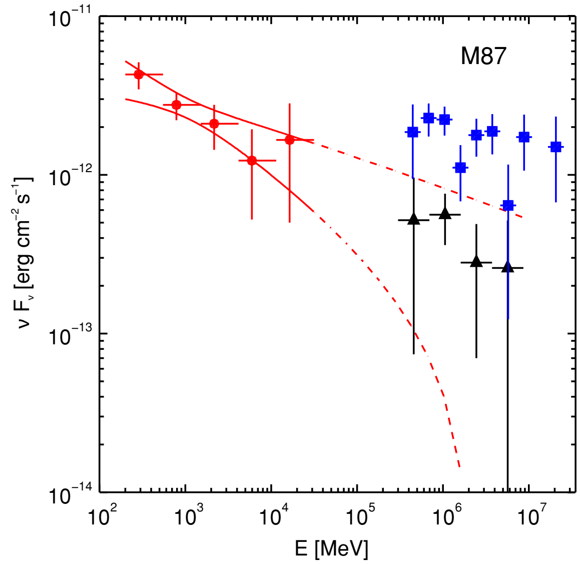

Figure 2. Observed LAT spectrum (red circles) with representative TeV measurements of M87 in a low state from the 2004 observing season (black triangles) and during a high state in 2005 (blue squares), both by HESS (Aharonian et al. 2006). The lines indicate 1σ bounds on the power-law fit to the LAT data as well as its extrapolation into TeV energies.

entire sky approximately every 3 hr. The initial LAT detection of M87 resulted from nominal processing of six months of all-sky survey data, as was applied to the initial three-month data set described in Abdo et al. (2009a), with a test statistic (Mattox et al. 1996), TS ~ 60. Including here an additional four months of data, the TS increased to 108.5, which is equivalent to a source significance $\sim\sqrt{\mathrm{TS}} = 10.4\sigma$. The resultant 10-month data set (2008 August 4–2009 May 31) corresponds to mission elapsed times (MET) 239557418 to 265420800. Our analysis followed standard selections of "Diffuse" class events (Atwood et al. 2009) with energies $E > 200$ MeV, a zenith angle cut of $<105°$, and a rocking angle cut of 43° applied in order to avoid Earth albedo γ-rays. *Fermi* Science tools[57] version v9r10 and instrumental response functions (IRFs) version `P6_V3_DIFFUSE` were used for the analysis.

A localization analysis with `GTFINDSRC` resulted in a best-fit position, R.A. = $187^{\circ}.722$, decl. = $12^{\circ}.404$ (J2000.0 equinox), with a 95% confidence error radius, $r_{95\%} = 0^{\circ}.086 = 5'.2$ (statistical only; $r_{68\%} = 3'.2$). To account for possible contamination from nearby sources, the model included all point sources detected at $> 5\sigma$ in an internal LAT nine-month source list within a region of interest (ROI) of $r = 15°$ centered on the γ-ray position. Galactic diffuse emission was modeled using GALPROP (Strong et al. 2004), updated to include recent gas maps and a more accurate decomposition into Galactocentric rings (galdef ID `54_59varh7S`). An additional isotropic diffuse component modeled as a power law was included. Figure 1 shows the resultant γ-ray source localization on a VLA radio image from Owen et al. (2000). The γ-ray source is positionally coincident with the known radio position of the M87 core (R.A. = $187^{\circ}.706$, decl. = $12^{\circ}.391$; Fey et al. 2004), with an offset ($0^{\circ}.020 = 1'.2$) that is a small fraction of the localization circle. Currently, the best estimate of the systematic uncertainty in $r_{95\%}$ is $2'.4$ (Abdo et al. 2009a), which should be added in quadrature to the determined statistical one.

Spectral analysis was performed utilizing an unbinned likelihood fit of the >200 MeV data with a power law ($dN/dE \propto E^{-\Gamma}$) implemented in the `GTLIKE` tool. This resulted in $F(>100\ \mathrm{MeV}) = 2.45\ (\pm 0.63) \times 10^{-8}$ photons cm^{-2} s^{-1} with a photon index, $\Gamma = 2.26 \pm 0.13$; errors are statistical only. The flux was extrapolated down to 100 MeV to facilitate comparison with the previous EGRET non-detection of $< 2.18 \times 10^{-8}$ photons cm^{-2} s^{-1} (2σ) from observations spanning the 1990s (Reimer et al. 2003). Thus, there is no apparent change in the flux (i.e., a rise) in the decade since the EGRET observations. Systematic errors of $(+0.17/-0.15) \times 10^{-8}$ photons cm^{-2} s^{-1} on the flux and $+0.04/-0.11$ on the index were derived by bracketing the energy-dependent ROI of the IRFs to values of 10%, 5%, and 20% above and below their nominal values at $\log(E(\mathrm{MeV})) = 2, 2.75$, and 4, respectively. The spectrum extends to just over 30 GeV where the highest energy photon is detected within the 95% containment. The LAT spectral data points presented in Figure 2 were generated by performing a subsequent likelihood analysis in five equal logarithmically spaced energy bins from 0.2 to 31.5 GeV. The 1σ bounds on the spectrum, obtained from the full >200 MeV unbinned likelihood fit, were extended to higher energies for comparison with previous TeV measurements (see Section 3).

Light curves were produced in 10-day (Figure 3) and 28-day (not shown) bins over the 10-month LAT data set. Considering the limited statistics, it was necessary to fix the photon index to the (average) fitted value in order to usefully gauge variability in the flux. Considering only statistical errors of all the binned data points with TS $\geqslant 1$ (1σ), a χ^2 test against the weighted mean fluxes of the 10-day and 28-day light curves resulted in probabilities, $P(\chi^2, \nu) = 22\%$ and 70%, respectively, indicating plausible fits to the tested hypothesis. We conclude that there is no evidence for variability over the period of observations.

A radial profile of the γ-ray source counts (not shown) was extracted for the total energy range (>200 MeV). The profile is consistent with that of a point source simulated at energies 0.2–200 GeV using the fitted spectral parameters above with a reduced $\chi^2 = 1.04$ for 20 degrees of freedom. The total

[57] http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/

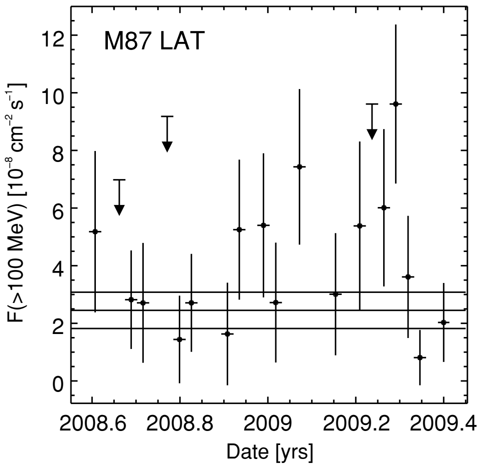

Figure 3. Light curve in 10-day bins obtained with the fitted photon index ($\Gamma = 2.26$) fixed. The average flux is indicated with the solid horizontal line and the dotted lines are $\pm 1\sigma$ about the average. Data points with TS < 1 (i.e., 1σ) are shown as upper limits.

$\sim 0.^{\circ}2$ extent of the 10's kpc-scale radio lobes of M87 (Figure 1; Owen et al. 2000) is comparable to the LAT angular resolution, $\theta_{68} \simeq 0.^{\circ}8 E_{\rm GeV}^{-0.8}$ (Atwood et al. 2009). Therefore, from the presently available data, we cannot disentangle (or exclude) a possible contribution of the extended radio features to the total γ-ray flux.

To gauge the X-ray activity of M87 over the duration of the LAT observations, we analyzed five new 5 ks *Chandra* ACIS-S images obtained in $\sim$6 week intervals between 2008 November and 2009 May (PI: D. E. Harris). The X-ray core fluxes (0.5–7 keV) in these monitoring observations, (1.2–1.6) $\times 10^{-12}$ erg cm^{-2} s^{-1} ($\sim$0.4–0.6 keV s^{-1} in the units of Figure 9 of Harris et al. 2009), are at the low end of the observed range over the last $\sim$7 years. Additionally, the fractional variability is small (σ/<flux>$\sim$ 0.1), indicating low X-ray activity in the core over the LAT observing period.

At milliarcsecond (mas) resolution in the radio band, M87 has been monitored with the VLBA at 15 GHz since 1995 as part of the 2 cm survey (Kellermann et al. 2004) and MOJAVE (Lister et al. 2009) programs.[58] These data were re-imaged uniformly at 0.6 mas $\times$ 1.3 mas (position angle $= -11^{\circ}$) resolution to match the additional map presented in Kovalev et al. (2007) resulting in 23 total measurements of the unresolved core flux up to the latest observation on 2009 January 7 (one of the *Chandra* exposures described above was obtained on the same day). This observation is the only one overlapping with the LAT data set and the peak flux of 1.05 Jy beam^{-1} is consistent with the average over all the measurements (1.11 ± 0.16 Jy beam^{-1}). An indication of the sensitivity of these data to detecting flaring core emission is that the high flux state observed in the detailed 43 GHz VLBA monitoring at the time of TeV flaring in 2008 (Acciari et al. 2009, see Section 3) is visible in the 15 GHz data as a single high point on 2008 May 1 (1.45 Jy beam^{-1}).[59] This only suggests a period of low activity in the radio core (as reflected in the X-ray data), as the single radio flux may not be representative of the entire 10-month LAT viewing period.

58 See http://www.physics.purdue.edu/MOJAVE/

59 Conversely, during the previous TeV flaring period spanning 2005 March–May (Aharonian et al. 2006), no comparable flare was visible in the VLBA 15 GHz core: 1.02 Jy beam^{-1} peak on April 21 and 0.98 Jy beam^{-1} on November 7. Instead, the flaring X-ray/optical/radio knot HST-1 (60 pc from the core, projected) was observed to peak in early 2005 (Harris et al. 2009), suggesting an association with the variable TeV source (Cheung et al. 2007).

3. DISCUSSION

In blazars, it is commonly believed that γ-rays are produced in compact emission regions moving with relativistic bulk velocities in or near the parsec scale core in order to explain the observed rapid variability and to avoid catastrophic pair production (e.g., Dondi & Ghisellini 1995). Consequently, it is natural to extend this supposition to radio galaxies (Chiaberge et al. 2001) which are believed to have jets oriented at systematically larger angles to our line of sight, thus constituting the parent population of blazars. Indeed, in the case of M87, a significant months timescale rise in the flux of the subparsec scale radio core was discovered with the VLBA (at 43 GHz) during a period in early 2008 when few day timescale TeV flaring was detected (Acciari et al. 2009). During this period of increased activity, a *Chandra* measurement of the subarcsecond scale X-ray nucleus also indicated a relatively higher flux than seen in past observations (Harris et al. 2009), thus signaling a common origin for the flaring emissions in the M87 nucleus. Therefore, during periods of lower γ-ray activity, the radio/X-ray core can also be considered a dominant source of the unresolved higher-energy emission, and we discuss this in the context of the LAT MeV/GeV detection.

In Figure 2, the LAT spectrum of M87 is plotted along with representative integrated TeV spectra from HESS (Aharonian et al. 2006). The TeV measurements cover periods when M87 was in its historical minimum (in 2004), and during a high state (in 2005; cf., Figure 3 in Acciari et al. 2008). Although the formal difference in the fitted photon indices of the TeV data at high and low states is not statistically significant ($\Gamma = 2.22 \pm 0.15$ and 2.62 ± 0.35, respectively), the LAT MeV/GeV spectrum ($\Gamma = 2.3$) connects smoothly with the low-state TeV spectrum. Taken together with the X-ray and radio measurements obtained during the LAT observation (Section 2), we view this as an indication that M87 is in an overall low γ-ray activity state during the considered period. In fact, no significant TeV flaring was detected in a preliminary analysis of 18 hr of contemporaneous VERITAS observations from 2009 January–April (Hui 2009).

M87 is the faintest γ-ray radio galaxy detected so far by the LAT with a $>$100 MeV flux ($\sim 2.5 \times 10^{-8}$ photons cm^{-2} s^{-1}) about an order of magnitude lower than in Cen A (Abdo et al. 2009c) and Per A (Abdo et al. 2009b); the corresponding $>$100 MeV luminosity, 4.9×10^{41} erg s^{-1}, is 4$\times$ greater than that of Cen A, but $>$200$\times$ smaller than in Per A. There is no evidence of intra-year or decade-timescale MeV/GeV variability in M87 (Section 2), in contrast to the $\gtrsim 7\times$ and $\sim 1.6\times$ larger observed LAT fluxes than the previous EGRET ones in the cases of Per A (Abdo et al. 2009b) and Cen A (Abdo et al. 2009c), respectively. The γ-ray photon index of M87 in the LAT band is similar to that of Per A ($\Gamma = 2.3$ and 2.2, respectively), while being smaller than observed in Cen A ($\Gamma = 2.9$; Abdo et al. 2009c). These sources are low-power (FRI) radio galaxies, and have broad low-energy synchrotron and high-energy inverse Compton (IC) components in their spectral energy distributions (SEDs) peaking roughly in the infrared and γ-ray bands, respectively. Low-energy-peaked BL Lac objects have similar shaped SEDs, with approximately equal apparent luminosities (e.g., Kubo et al. 1998). As FRI radio galaxies are believed to constitute the parent population of BL Lacs in unified schemes (Urry & Padovani 1995), the overall similarity of their SEDs is not surprising.

We construct a SED for M87 (Figure 4) using the LAT γ-ray spectrum and the overlapping 2009 January 7 *Chandra* and

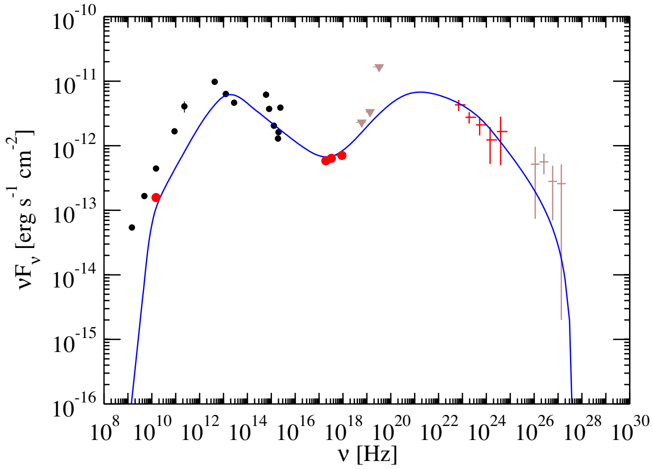

Figure 4. SED of M87 with the LAT spectrum and the 2009 January 7 MOJAVE VLBA 15 GHz and *Chandra* X-ray measurements of the core indicated in red. The non-simultaneous 2004 TeV spectrum described in Figure 2 and *Swift*/BAT hard X-ray limits (Section 3) of the integrated emission are shown in light brown. Historical measurements of the core from VLA 1.5, 5, 15 GHz (Biretta et al. 1991), IRAM 89 GHz (Despringre et al. 1996), SMA 230 GHz (Tan et al. 2008), *Spitzer* 70, 24 μm (Shi et al. 2007), Gemini 10.8 μm (Perlman et al. 2001), *Hubble Space Telescope HST*) optical/UV (Sparks et al. 1996), and *Chandra* 1 keV from Marshall et al. (2002, hidden behind the new measurements) are plotted as black circles. The VLBA 15 GHz flux is systematically lower than the historical arcsec-resolution radio to infrared measurements due to the presence of intermediate scale emission (see, e.g., Kovalev et al. 2007). The blue line shows the one-zone SSC model fit for the core described in Section 3.

VLBA measurements of the core. Also plotted are historical radio-to-X-ray fluxes of the core (see Sparks et al. 1996; Tan et al. 2008) measured at the highest resolutions at the respective frequencies. The core is known to be variable, with factors of $\sim$2 changes on months timescales common in the optical and X-ray bands (Perlman et al. 2003; Harris et al. 2009). To help constrain the overall SED at frequencies between the X-ray and LAT measurements, we determined integrated 3σ upper limits in three hard X-ray bands (following Ajello et al. 2008) based on the *Swift*/BAT data set in Ajello et al. (2009), including about another additional year of exposure (i.e., $\sim$4 years total from 2005 March–2009 January).

The broadband SED is fitted with a homogeneous one-zone synchrotron self-Compton (SSC) jet model (Finke et al. 2008) assuming an angle to the line of sight, $\theta = 10^\circ$, and bulk Lorentz factor, $\Gamma_b = 2.3$ (Doppler factor, $\delta = 3.9$), consistent with observations of apparent motions of $\gtrsim 0.4c$ ($\Gamma_b > 1.1$) in the parsec-scale radio jet (Ly et al. 2007). A broken power-law electron energy distribution $N(\gamma) \propto \gamma^{-p}$ is assumed, and the indices, $p_1 = 1.6$ for $\gamma = [1, 4 \times 10^3]$ and $p_2 = 3.6$ for $\gamma = [4 \times 10^3, 10^7]$ are best guesses based on the available core measurements. The normalization at low energies is constrained by the single contemporaneous VLBA 15 GHz flux which is measured with $\sim 10^2$–$10^3\times$ better resolution than the adjacent points. The source radius, $r = 1.4 \times 10^{16}$ cm $= 4.5$ mpc, is chosen to be consistent with the best VLBA 43 GHz map resolution ($r < 7.8$ mpc $= 0.1$ mas; Junor et al. 1999; Ly et al. 2007) and is of order the size implied by the few day timescale TeV variability (Acciari et al. 2009). For the source size adopted, internal γ–γ absorption is avoided so that the LAT spectrum extends relatively smoothly into the TeV band, consistent with the historical-minimum flux detected by HESS (Aharonian et al. 2006) and the preliminary upper limit of <1.9% Crab from VERITAS observations (Hui 2009) contemporaneous with the LAT ones.

In the SSC model, the magnetic field is $B = 55$ mG and assuming the proton energy density is $10\times$ greater than the electron energy density, the total jet power is $P_j \sim 7.0 \times 10^{43}$ erg s^{-1}. The jet power is particle dominated, with only a small contribution from the magnetic field component ($P_B \sim 2 \times 10^{40}$ erg s^{-1}). In comparison, the total kinetic power in the jet is $\sim$few $\times 10^{44}$ erg s^{-1} as determined from the energetics of the kpc-scale jet and lobes (Bicknell & Begelman 1996), and is consistent with the jet power available from accretion, $P_j \lesssim 10^{45}$ erg s^{-1} (Reynolds et al. 1996; Di Matteo et al. 2003). These power estimates are similar to those derived for BL Lacs from similarly modeling their broadband SEDs (e.g., Celotti & Ghisellini 2008).

As applied to M87, such single-zone SSC emission models also reproduce well the broadband SEDs up to MeV/GeV energies in the radio galaxies Per A (Abdo et al. 2009b) and Cen A (Chiaberge et al. 2001). In this context, the observed MeV/GeV γ-ray fluxes of blazars appear to be correlated with their compact radio cores (Abdo et al. 2009c; Kovalev et al. 2009), suggesting a common origin in the Doppler boosted emission in the subparsec scale jets. The fact that the three radio galaxies detected by the LAT so far have amongst the brightest ($\gtrsim$1 Jy) unresolved radio cores, in line with these expectations (Ghisellini et al. 2005), lend evidence for a common connection between the γ-ray- and radio-emitting zones in such jets.

It should be emphasized that these observations are not simultaneous and particularly, the TeV emission is known to be variable on year timescales, so other emission components may contribute to the variable emission. Therefore, although not strictly required, more sophisticated models over the single-zone one presented can reproduce or contribute to the observed emission. In particular, the beaming requirements in the one-zone SSC modeling of the three known γ-ray radio galaxies are systematically lower than required in BL Lacs, suggesting velocity profiles in the flow (Chiaberge et al. 2001). Such models (Georganopoulos et al. 2005; Tavecchio & Ghisellini 2008) have in fact been used to fit the SED of M87 in addition to models based on additional spatial structure (e.g., Lenain et al. 2007). Protons, being inevitably accelerated if they co-exist with electrons in the emission regions, probably dominate energetically and dynamically the jets of powerful active galactic nucleus (AGN; e.g., Celotti & Ghisellini 2008). Applying the synchrotron-proton blazar model (Mücke et al. 2003; Reimer et al. 2004) to the quiescent M87 data set yields reasonable agreement model fits that support a highly magnetized compact emission region with approximate equipartition between fields and particles and a total jet power comparable with the above estimates, where protons are accelerated up to $\sim 10^9$ GeV.

Outside of the pc-scale core, the well-known arcsecond-scale jet (e.g., Biretta et al. 1991; Marshall et al. 2002; Perlman & Wilson 2005) is also a possible source of IC emission. As both the LAT and TeV telescopes are unable to spatially resolve emission on such small scales, the expected spectral and temporal properties of the predicted emission must be examined. On the observed scales, the dominant seed photon source is the host galaxy starlight, and such an IC/starlight model applied to one of the brightest resolved knots in the jet—knot A, $\sim$1 kpc projected distance from the core—results in a spectrum peaking at TeV energies (Stawarz et al. 2005), thus producing a harder MeV/GeV spectrum than observed by the LAT. Even closer to the core ($\sim$60 pc, projected), the superluminal knot

HST-1 ($>4c$–$6c$; Biretta et al. 1999; Cheung et al. 2007) is a more complex case. This knot is more compact than knot A, and its IC emission is expected to be further enhanced by the increased energy densities of the surrounding circumnuclear and galactic photon fields, as well of the comoving synchrotron radiation (Stawarz et al. 2006). The radio/optical/X-ray fluxes of HST-1 have been declining since its giant flare peaked in 2005 (Harris et al. 2009), with current X-ray fluxes comparable to its preflare levels in 2002. Considering the variable and compact nature of the source (with observed months doubling timescales implying $r \lesssim 22\delta$ mpc; cf. footnote 59), the predicted IC spectrum has a complex temporal and spectral behavior. In the absence of detailed contemporaneous measurements, its possible role in the production of the LAT observed MeV/GeV emission is unclear.

Continued LAT monitoring of M87 coordinated with multi-wavelength observations can extend the current study of "quiescent" emission to possible flaring, in order to further address the physics of the radiation zone. While the extragalactic γ-ray sky is dominated by blazars (Hartman et al. 1999; Abdo et al. 2009c), this optimistically indicates an emerging population of γ-ray radio galaxies. Other examples, including the few possible associations with EGRET detections like, NGC 6251 (Mukherjee et al. 2002) and 3C 111 (Sguera et al. 2005; Hartman et al. 2008) await confirmation with the LAT, and more radio galaxies are expected to be detected at lower fluxes. This holds great promise for systematic studies of relativistic jets with a range of viewing geometries in the high-energy γ-ray window opened up by the *Fermi*-LAT.

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