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Permalink
https://escholarship.org/uc/item/2096d66b

Journal
ASTROPHYSICAL JOURNAL, 879(2)

ISSN
0004-637X

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Publication Date
2019-07-10

DOI
10.3847/1538-4357/ab23ee

Peer reviewed
The Extragalactic Gamma-Ray Background from Core Dominated Radio Galaxies

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Received ________________, accepted ________________

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ABSTRACT

Recent radio surveys have discovered a large number of low luminosity core dominated radio galaxies that are much more abundant than those at higher luminosities. These objects will be too faint in $\gamma$-rays to be detected individually by Fermi. Nevertheless, they may contribute significantly to the unresolved extragalactic $\gamma$-ray background. We consider here the possible contribution of these core dominated radio galaxies to the diffuse extragalactic $\gamma$-ray background. Using published data available for all 45 of the radiogalaxies listed as detected counterparts in the Fermi FL8Y source list update to the 3FGL catalog, we have searched for radio maps which can resolve the core flux from the total source flux. Using high resolution radio maps we were able to obtain core fluxes for virtually every source. We then derived a relation between core radio flux and $\gamma$-ray flux that we extrapolated to sources with low radio luminosities that are known to be highly core dominated. We then employed a very recent determination of the luminosity function for core dominated radio galaxies in order to obtain the contribution of all possible $\gamma$-ray emitting radio galaxies to the unresolved extragalactic $\gamma$-ray background. We find this contribution to be a possibly non-negligible, 4% - 18% of the background.

Subject headings: Gamma rays: diffuse background – Gamma rays: radio galaxies: active galaxies
1. Introduction

The Large Area Telescope on the Fermi Gamma-ray Space Telescope (hereafter called Fermi) has measured the diffuse unresolved extragalactic $\gamma$-ray background (hereafter, EGB) at energies between 0.1 GeV and 820 GeV (Ackermann et al 2015). The photon spectrum of the EGB is found to follow an approximate power-law of spectral index $\sim 2.3$ below $\sim 200$ GeV, with a total flux above 0.1 GeV of $\sim 7 \times 10^{-6}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. It appears that $\sim 85\%$ of the EGB at energies above 50 GeV is from unresolved blazars (Ackermann et al. 2016). Below 50 GeV, the EGB may be made up of various unresolved extragalactic $\gamma$-ray sources such as blazars (e.g., Stecker 1993; Padovanni et al. 1993; Stecker & Salamon 1996; Stecker & Venters 2011) and star forming galaxies (Pavlidou & Fields 2001,2002; Stecker 2007; Fields 2010; Makiya et al. 2011; Stecker & Venters 2011; Tamborra et al. 2014; Linden 2017). Star forming galaxies emit $\gamma$-rays at energies above 0.1 GeV, such $\gamma$-rays being produced by interactions of cosmic rays accelerated in supernova explosions of young massive stars with interstellar gas (Stecker 1971, 1976). If one lists the number of $\gamma$-ray point sources by AGN type one finds that the gamma-ray sky is dominated by radio-loud blazars that have their jets aligned within $\sim 20^\circ$ of the direction of the Earth. No radio quiet AGN, other than nearby ones with active star formation, have been detected by Fermi.

In addition to blazars and star forming galaxies, a number of $\gamma$-ray emitting radio galaxies have been detected by Fermi, indicating that radio galaxies can also contribute to the EGB (e.g., Inoue 2012; di Mauro et al. 2014; Hooper et al. 2016). These galaxies are believed to be AGN whose jets are "mis-aligned" with the direction of the Earth (Inoue 2011).

In this study, we specifically consider the more recently discovered relatively abundant classes of low luminosity core dominated radio galaxies. In order to examine this hypothesis
we derive a new relation between core radio and γ-ray luminosity based on an updated list of Fermi-detected radio galaxies. This relation implies that lower luminosity γ-ray emitting radio galaxies are expected to have proportionally lower γ-ray luminosities so that they cannot be detected individually by Fermi. However, their high relative abundance implies that they can contribute to the unresolved (diffuse) γ-ray background. In order to examine this hypothesis we need to derive a new relation between core radio and γ-ray luminosity.

In Section 2 we discuss how we determined estimated core radio fluxes from radio maps for the γ-ray emitting radio sources given in the Fermi FL8Y source list. The FL8Y source list, which is based on the first eight years of Fermi data in the 100 MeV - 1 TeV energy range, includes 5523 sources observed by Fermi as having a significance > 4σ.

In section 3 we use the expanded Fermi FL8Y source list, together with the results from Section 2, to derive a new log-linear relation between γ-ray luminosity and core radio luminosity for Fermi-detected radio galaxies.

In Section 4 we make the case for the importance of the potential contribution of classes of low luminosity radio sources to the diffuse EGB; such sources being too weak to be individually detected by Fermi.

Section 5 gives our choice for luminosity functions for core dominated radio galaxies at different redshifts. This includes the classes of low luminosity radio sources considered in Section 4.

Section 6 outlines our calculation of the EGB from γ-ray emitting radio galaxies. Section 7 concludes with a discussion of our results.
2. Core Luminosities for our Data Set of Gamma-ray Emitting Radio Galaxies

As a first step in our program to determine the EGB from core dominated radio galaxies, we examined the published radio and γ-ray data available for all 45 of the radio galaxies listed as detected counterparts in the Fermi FL8Y source list update to the Fermi 3FGL source catalog. We employed this updated list of 45 sources, in conjunction with their corresponding radio data discussed in Section 2, to derive a new radio (core) to gamma-ray luminosity relation.

In order to obtain the core fluxes for these 45 sources, we searched for radio maps of these sources which can resolve the core flux from the total source flux. For virtually every source we were able to find these measurements. We sought radio observations the highest angular resolution available. In the majority of cases this was provided by interferometry at the Very Large Array (VLA). Nearly all of the sources have a detectable compact core with a measured flux. The core observed fluxes range from making up > 90% of the total source flux, down to 10% or less.

In a few cases, no distinct ‘core’ component is visible. For such radio galaxies we used radio maps to set strict upper limits to the possible core flux, which is typically 5% or less of the total flux. Most of the maps were made at an observing frequency of 5 GHz. Where

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1 The FL8Y list is based on 8 years of sky survey data. It is a precursor to the forthcoming 4FGL catalog.

2 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

3 For those sources which are too far south for the VLA to observe, we found maps from the Australia Telescope Compact Array (ATCA). We were also able to obtain results from Multi-Element Radio Linked Interferometer Network (MERLIN).

4 Only 3 of the Fermi-detected radiogalaxies show no detectable cores, only diffuse extended (usually double) radio emission: and MRC0522-239, MRC1303-215, and MRC 2327-215. For these
these were not available, we used 1.4 GHz maps. References to each of the publications used to determine the core fluxes are given in Table 1 and more fully in the reference list.

3. Radio Luminosity - Gamma Ray Luminosity Correlation

We now derive a relationship between the expected $\gamma$-ray luminosity of a radio galaxy and its radio luminosity. Fortunately, such a relationship has been found to exist that spans the entire radio luminosity range, regardless of type (such as FRI and FRII), provided one considers only the core luminosity of the radio sources (here designated by $L_R$) rather than their total luminosity (Inoue 2011; di Mauro et al. 2014; Hooper et al. 2016). This relation can be understood conceptually. The radio core emission is directly associated with the power produced by non-thermal processes in the central engine of the AGN in the vicinity of the black hole and the base of the jet. The physics of such jets is analogous to that of the more familiar $\gamma$-ray emitting blazars such as BL Lac objects. In fact, it appears that Fermi-detected $\gamma$-ray emitting blazars are more core dominated than those not detected by Fermi (Pei et al. 2018).

We have updated the relation between $\gamma$-ray luminosity and core radio luminosity using our expanded data set as discussed in the previous section. We therefore will adopt the reasonable assumption of extrapolating our new relation between radio core and $\gamma$-ray luminosities to lower core radio luminosities.

For $\gamma$-ray emitting radio galaxies, di Mauro et al. (2014) and Hooper et al. (2016) found a relation between the radio (core) and $\gamma$-ray luminosities. Those authors found an approximate log-linear relation to hold, i.e.

$$\log(L_\gamma) = A \log(L_R) + B.$$  \hspace{1cm} (1)

we adopted conservative upper limits to the possible flux of a faint core.
Subsequent to those previous determinations, the total Fermi sky exposure has doubled. In addition to this increase in exposure, the entire dataset recently underwent a full reproprocessing, applying refined instrumental calibrations and event selections. This recalibration, which followed procedures as described in (Atwood et al. 2013), lead to significant improvement in sensitivity and source localization and resulted in the FL8Y source list used here.

We have updated the relation between γ-ray luminosity and core radio luminosity using our expanded data set as discussed in Section 2 in order to derive a new core radio to γ-ray luminosity relation. Using our new data set we find a best fit to the relation shown in Fig. 1 to be of the form of equation (1) with derived values of $A = 0.89$ and $B = 7.15$. Figure 1 shows the luminosity data overlaid with our derived correlation. The previous results of di Mauro et al. (2014) and Hooper et al. (2016), are also shown for comparison in Figure 1.

4. Low Luminosity Core Dominated Radio Galaxies

In roughly the past decade populations of low luminosity compact core dominated radio sources have been revealed through a combination of wide field-of-view $\sim$ GHz surveys and follow up interferometric mapping. These abundant sources have been designated ”miniature RGs” or ”Core Galaxies” (CoreG) with typical luminosities in the range $10^{20} - 10^{22}$ W/Hz at 1.4 GHz and ”FR0 galaxies” with luminosities in the range $10^{22} - 10^{24}$

\footnote{Previous results were based on the smaller (3FGL) sample with about half the number of detections, and both incorporated upper limits into their analysis. In calculating the parameters of the luminosity correlation, we have not included sources with only γ-ray flux upper limits. However, our result agrees well with that of di Mauro (2014).}
W/Hz at 1.4 GHz (Balmaverde & Capetti 2006). These highly core-dominated radio sources are found mostly in luminous, red, early type galaxies (Herrera Ruiz et al. 2017; Baldi, Capetti, & Massaro, 2018). They are classified predominantly as LERGs (low-excitation radio galaxies) (see, e.g. Best & Heckman (2012a). FR0 galaxies, although of lower radio luminosity than FRI galaxies, have been found to be five times more numerous than FRI galaxies in the local universe (Baldi et al. 2018).

Core G and FR0 galaxies are faint radio sources, having luminosities below $10^{25} \text{ W/Hz}$. Because of their relatively low luminosity, they are expected to be extremely difficult to detect as individual $\gamma$-ray sources, as follows from relation (1). In fact, even at radio frequencies these galaxies have not been observed at redshifts above $\sim 0.5$. However, owing to their abundance, we consider core-dominant Core G and FR0 galaxies to be candidates to contribute significantly to the unresolved extragalactic $\gamma$-ray background.

We have searched the literature as well as the Sloan Digital Sky Survey (SDSS) database for optical spectroscopy of the Fermi-detected radio galaxies. The majority of them have an available optical spectrum which allows us to classify $\sim 93\%$ of these radio galaxies as either “HERGs” (high excitation radio galaxies) or “LERGs”. Whereas HERGs typically have accretion rates of $\sim 1$-10 % Eddington, LERGs have typical accretion rates below $\sim 1 \%$ Eddington (Heckman & Best 2012). Using their optical spectra to classify the radio galaxies detected by Fermi, we classify $\sim 70\%$ of them as LERGs and $\sim 30\%$ as HERGs. The later are usually indicated by their broad permitted lines, which make them either quasars or Seyfert 1 AGN.

Baldi et al. (2018) chose their sample of 108 FR0 galaxies to be limited to redshifts

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6There has been one claimed detection of an FR0 designated as Toll 326-379 as a $\gamma$-ray source (Grandi, Capetti & Baldi 2016). However, with the refined positional determination of this gamma-ray source in the FL8Y source list the association with Toll 1326-379 is now very questionable.
$z \leq 0.05$ to optimize spatial resolution, and to fluxes $F_r \geq 5$ mJy. The Baldi et al. FR0 sample peaks in the range $20$ mJy $\geq F_r \geq 30$ mJy. Given their resolution, they find their observed FR0s to be very strongly core dominated.

We have examined optical spectra of the FR0 sources which have available observations from SDSS. Of those, somewhat more than 80% are likely LERGs. Their population is therefore likely to show the relatively weak redshift dependence typical of LERGs (Best, et al. 2014; Pracy et al. 2016; Yuan et al. 2017), in contrast with the strong redshift-evolution seen for HERGs. \footnote{Given the LERG predominance among the FR0 sample, we note that the converse is not necessarily true, i.e., one cannot conclude LERGs as a population are not predominantly FR0s.}

Since FR0s are low redshift sources, with an expected weak redshift dependence, we make the reasonable conservative assumption of a Euclidean source count for these sources. This assumption is supported by the fact that FR0s are predominantly LERGs. It is known that LERGs have little redshift dependence (e.g., Pracy et al. 2016).

Figure 2 shows the integral source count distribution obtained by Baldi et al. (2018) for the 108 FR0 galaxies in their sample. A Euclidean distribution extrapolation is also shown in the figure. Thus, it would be difficult to obtain the contribution of FR0s alone to the EGB from this sample.

We wish to estimate the possible contribution of all core dominated radio sources to the EGB based on a more complete picture. This would include low luminosity sources such as FR0s, but also higher luminosity core dominated sources. Our method for doing this will be discussed in the next section.
5. Luminosity Function (LF) of Radio Core Emission

Traditionally galaxy radio luminosity functions are derived based on the total; i.e. spatially integrated or, more commonly unresolved radio emission. In recent years combined radio and spectroscopic surveys have led to statistically complete samples comprising \( \sim 10^4 \) objects (e.g., Best & Heckman (2012); Pracy et al. 2016) from which rigorously determined radio luminosity functions have been derived, but most of these sample objects are unresolved.

As discussed earlier, the core radio emission in radio galaxies is what is physically most directly associated with the central AGN activity. As such a luminosity function based on a large, flux limited statistically complete sample of resolved radio galaxy core luminosities would be greater value for many applications involving AGN and related high-energy properties such as their \( \gamma \)-ray emission and contribution to the EGB. In practical terms however, the task of obtaining VLBI maps for a large sample of say \( 10^3 \) to \( 10^4 \) galaxies is a daunting one, and thus progress has remained limited. The previous efforts to estimate the radio-galaxy contribution to the EGB have invoked scaling relations to estimate the radio core luminosity function from the total one (e.g., Fig 4 of di Mauro et al. 2014), however relations have necessarily been based on limited statistics. Thus, uncertainties are inherent in estimates of the EGB.

Recently, Yuan et al (2018) have made progress in improving estimates of the core radio luminosity function by employing a large sample of radio galaxies in conjunction with statistical methods. They find a relatively weak luminosity dependent evolution in comparison to other derivations of the total luminosity functions. We note that their derivation incorporates both FRI and II subclasses which are delineated in terms of luminosity, but the total-to-core correction for the combined luminosity distribution is smoothly interpolated. The sample also extends to the low-luminosity extreme core
dominant FR0 population, which may in fact be the predominant population locally (Baldi, Capetti, A. & Massaro, 2018). The resulting radio galaxy core luminosity function has thus been obtained by Yuan et al. (2018). Yuan et al. also show that relatively low luminosity, low redshift radio sources below $10^{25}$ W/Hz are core dominated. This luminosity function at low luminosities is consistent with the Euclidean number flux distribution shown in Figure 2.

We thus chose to compute our estimate of the radio galaxy contribution to the EGB based on the Yuan et al (2018) luminosity function. We use the LFs for sources at higher redshifts as also derived by Yuan et al (2018) (see Sect. 4 Figure 4). The higher redshift LFs derived by Yuan et al. show a very weak redshift evolution as typical of LERGS, with the number density peaking at $z \sim 0.8$. This resonates with our results in Section 4 where we found that both FR0s and $\gamma$-ray -loud radio galaxies are primarily LERGs.

6. Gamma-ray Background from Core Dominated CoreG, FR0 and FRI Galaxies

We proceeded by deriving a $\gamma$-ray luminosity function based on our $L_\gamma$ to $L_R$ correlation presented in section 3 and the radio galaxy core luminosity function of Yuan (2018) as discussed in Section 5. Specifically, weve used the parametric form of that LF and their fitted parameters for the radio galaxy population. From that we compute the $\gamma$-ray LF as

$$\Phi_\gamma(L_\gamma, z) = \Phi_R(L_R(L_\gamma), z) d \log L_R d \log L_\gamma,$$

with equation (2) being evaluated using the relation (1), extrapolated to lower luminosities than were detected by Fermi. Here and elsewhere $L_R$ refers to the core luminosity at a frequency of 5 GHz. We then compute the EGB contribution at a given energy according equation (3), except that we have not included the photon-photon opacity term. Also,
we have included a point source detection efficiency term which effectively removes the contribution from the brightest sources. Such sources would presumably be above the point-source threshold such as the 45 detections used in our gamma-to-radio luminosity relation and would be masked in the empirical EGB measurement process. For this procedure we follow the methodology of Abdo et al. (2010).

We now calculate the $\gamma$-ray background from core dominated radio galaxies. We assume that these sources have $\gamma$-ray spectra of approximate power-law form $KE^{-\Gamma}$ in the energy range $0.1 < 100$ GeV. We assume a distribution of $\gamma$-ray spectral indexes, $\Gamma$, for the 45 non-blazar radio loud AGN taken from the Fermi FL8Y compilation, fit to a Gaussian distribution with $\sigma = 0.35$ around a mean value of 2.3. This is shown in Figure 3. Our Gaussian assumption produce a slightly concave $\gamma$-ray spectrum (e.g., Stecker & Salamon 1996). We note that, despite the limited statistics, this our mean value matches precisely the measured EGB slope over the nominal 1-100 GeV range (Ackermann et al. 2015).

We use the luminosity function $\Phi_R(L, z)$ taken from Yuan et al. (2018) together with equation (2) to obtain the $\gamma$-ray luminosity function for core dominated radio galaxies. The $\gamma$-ray background is then given by

$$I(E_\gamma) = \int_{\Gamma_{\min}}^{\Gamma_{\max}} \frac{dn(\Gamma)}{d\Gamma} d\Gamma \int_{\gamma_{\min}}^{\gamma_{\max}} dz \int_{L_{\gamma,\min}}^{L_{\gamma,\max}} \frac{dL_\gamma}{\ln(10)L_\gamma} dV \Phi_{\gamma,Core}(L_\gamma, z) \frac{dE_\gamma}{dE_\gamma} (1 + z)E_\gamma, z \ e^{-\tau(E_\gamma, z)} \ (3)$$

(Salamon & Stecker 1994). Here, $\tau(E_\gamma, z)$ is absorption coefficient from $\gamma$-$\gamma$ pair production. Here we can take $\tau = 0$ for local sources with $\gamma$-ray energies less than $\sim 100$ GeV (Stecker, Scully & Malkan 2016). In the context of the standard $\Lambda$CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km sec$^{-1}$ Mpc$^{-1}$ the volume element

$$\left| \frac{dV}{d\Omega dz} \right| = \frac{c}{H_0} \left( \sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda} \right)^{-1}. \ (4)$$
7. Conclusions

Using radio maps we determined estimated core radio fluxes for the $\gamma$-ray emitting radio sources given in the expanded Fermi FL8Y source list. We used those results, to derive a new log-linear relation between $\gamma$-ray luminosity and core radio luminosity for Fermi-detected radio galaxies. We then considered the importance of the potential contribution of the recently studied classes of low luminosity radio sources to the diffuse GRB; such sources being too weak to be individually detected by Fermi. Using luminosity functions for core dominated radio galaxies at different redshifts, including the classes of low luminosity sources discussed in Section 4, we determined the contribution to the EGB from unresolved radio galaxies.

In order to calculate the EGB from core dominated radio galaxies, we carried out the integration of equation (3) over the range of observed spectral indices and with limits of integration in redshift and luminosity that covered the pertinent ranges. The $\gamma$-ray luminosity range that corresponds to the range of radio galaxy core luminosities (in erg/s) $36.0 < \log L_{\gamma} < 45.0$ for $\gamma$-rays in the energy range between 0.1 and 300 GeV see Figure 1. We evaluated the comoving volume integration from redshift $z = 0$ to $z = 3.0$.

Aside from our basic assumption regarding the low-luminosity core-dominant radio galaxy population as $\gamma$-ray emitters, the largest source of uncertainty in our calculation is the inherent scatter in the $\gamma$-ray-to-radio luminosity correlation as given by equation (1). This scatter is shown in Figure 1. To quantify this scatter, we considered a parallel band of uncertainty about the red curve of Fig. 1 spanning a factor of 2 (or 0.3 dex). We then computed the EGB, separately varying the parameters $A$ and $B$ in equation (1), with the curves constrained to lie within this certainty band. This leads to a range of EGB flux values from $\sim 11\% \pm 7\%$ of the EGB between 100 MeV and 100 GeV. This is indicated by the pink uncertainty band depicted in Figure 5.
In comparing our results with the unresolved EGB derived by the Fermi collaboration (referred to by Ackermann et al. 2015 as the IGRB), we note that the spectral index of the observed background is consistent with $E^{-2.3}$ so that the fraction of the background that we may attribute to core dominated radio galaxies is roughly independent of energy. However, the unresolved background derived by Ackermann et al. (2015) has a steep drop off above $\sim 350$ GeV. This drop off is probably due to a combination of (a) decreased sensitivity at the highest energies, (b) uncertainty in the analysis of the galactic foreground, and (c) some possible absorption from interactions with EBL photons (e.g., Stecker, Scully and Malkan 2016). For this reason, we do not calculate our results for energies above $\sim 100$ GeV. In this regard, we note that the Fermi group has determined that $\sim 85\%$ of the unresolved $\gamma$-ray background above 50 GeV is from blazars (Ackermann, M. et al. 2016).

We note that the Fermi upper limits on non-detected radio galaxies (Di Mauro et al. 2014) are consistent with relation (1) within our error band. Thus, while it is possible that not all core-dominated radio sources are $\gamma$-ray sources, our hypothesis and conclusions are reasonable.

On the other hand, we also note that the LF that we have used, taken from Yuan et al. (2018), may underestimate the number of lower luminosity radio sources, e.g., FR0s, owing to incompleteness. The LF below the knee of the LF may actually be steeper than assumed (see e.g. Falcke, Körding & Nagar 2004).

We conclude that the total $\gamma$-ray flux from core dominated radio galaxies can account for a minor, but non-negligible, 4% – 18% of the $\gamma$-ray background over the main energy range observed by Fermi. Together with the contributions from blazars and star forming galaxies (e.g., Stecker & Venters 2011), the entire observed diffuse $\gamma$-ray background can reasonably be accounted for.
| Fermi ID | Source ID | $S_\text{core}$ (Jy) | Ref.* | Tel/Array (HERG/LERG) |
|----------|-----------|----------------------|-------|----------------------|
| FL8Y J0030.6-0212 | SDSS J002900.98-01134 | 0.23 | Lee17 | ATCA 20 GHz LERG |
| FL8Y J0057.7+3022 | NGC 315 | 1.4 | Mack97 | Effelsberg LERG |
| FL8Y J0308.4+0407 | MRC 0305-039 = NGC 1218 | 0.7 | Unger84 | Merlin HERG |
| FL8Y J0316.9+4120 | IC 310 | 0.17 | Ahnen17 | VLA LERG |
| FL8Y J0319.8+4130 | NGC 1275 | 3-28 | Condon86 | VLA HERG |
| FL8Y J0322.6-3712e | MRC 0320-373 = NGC 1316 = Fornax A | 0.12 | Fomalont89 | VLA LERG |
| FL8Y J0334.3+3920 | 4C 39.12 | 0.43 | Liuzzo13 | VLA-8GHz LERG |
| FL8Y J0418.5+3810 | 3CR 111 | 1.2 | Hardcastle88 | VLA HERG |
| FL8Y J0433.0+0522 | MRC 0430+052 = 3C 120 | 1 | Fey96 | VLBA HERG |
| FL8Y J0519.7-4546 | 3C 189 = Pictor A | 15.4 | Tingay03 | ATCA 5 GHz HERG |
| FL8Y J0521.2+1637 | 3C 138 | 0.88 | Akujor91 | MERLIN HERG |
| FL8Y J0522.9-3628 | MRC 0521-365 | 1 | Lee16 | VLA HERG |
| FL8Y J0524.7-2405 | MRC 0522-239 | <0.5 | Kapahi98 | VLA ? |
| FL8Y J0623.9-3631 | MRC 0620-526 | 1.2 | Chhetri13 | ATCA 20 GHz LERG |
| FL8Y J0627.1-3529 | MRC 0625-354 | 0.5 | Morganti97 | VLA LERG |
| FL8Y J0708.9-3616 | MRC 0707-35 | 0.045 | Saikia99;Yuan+Wang'12 | ATCA 5 GHz ? |
| FL8Y J0758.7+3746 | 3C 189 = NGC 2484 | 0 | Condon91 | 5 GHz LERG |
| FL8Y J0840.8+1315 | 3C 207 | 0.35 | Kharb10 | VLA HERG |
| FL8Y J0858.3+1409 | 3C 208 | 0.51 | Bridle94 | VLA HERG |
| FL8Y J0934.3+3926 | 3C 221 | <0.4 | Vigotti99 | 5 GHz ? |
| FL8Y J1040.5+0617 | SDSS J103928.21+05361 | 0.2 | Kozei11 | 1.4 GHz LERG |
| FL8Y J1053.6+4930 | SDSS J105344.12+49295 | 0.3 | vanVelzen15 | VLA LERG |
| FL8Y J1144.9+1937 | 3C 264 = NGC 3862 | 0.4 | Bridle81 | VLA LERG |
| FL8Y J1215.9+0548 | 3C 270 = NGC 4261 | 0.3 | Jones97 | VLA LERG |
| FL8Y J1230.8+1223 | 3C 274 = M 87 | 3.9 | Kharb10 | VLA LERG |
| FL8Y J1244.5+1616 | 3C 275.1 | 0.2 | Fernini14 | VLA HERG |
| FL8Y J1312.6+4828 | SDSS J130248.70+4755105 | 0.033 | Best12b | VLA LERG |
| FL8Y J1306.4+1112 | SDSS J130619.24+11133 | 0.2 | Lin10 | VLA LERG |
| FL8Y J1307.7-2149 | MRC 1303-215 | 0.1 | Kapahi98 | VLA LERG |
| FL8Y J1325.5-4301 | MRC 1322-427 | 7 | Yuan12 | VLA HERG |
Table 1—Continued

| Fermi ID     | Source ID       | $S_{\text{core}}$ (Jy) | Ref. | Tel/Array | (HERG/LERG) |
|--------------|-----------------|------------------------|------|-----------|-------------|
| FL8Y J1331.0+3031 | 3C 286          | 5.5                    | An04 | VLA       | HERG        |
| FL8Y J1346.3-6027   | Cen B           | 2–6                    | Chherti13 | ATCA     | LERG        |
| FL8Y J1350.8+3033   | 3C 293 = UGC 8782 | 1.55                  | Joshi11 | VLA     | LERG        |
| FL8Y J1428.5+4240   | SDSS J142832.60+42402 | 0.2                   | Liuzzo13 | VLA     | LERG        |
| FL8Y J1443.0+5201   | 3C 303          | 0.13                   | Hardcastle88  | VLA     | HERG        |
| FL8Y J1454.2+1622   | 3C 306 = IC 4516 | 0.002                  | Condon91 | VLA     | LERG        |
| FL8Y J1459.0+7139   | 3C 309.1        | 2.4                    | Yuan18 | VLA     | HERG        |
| FL8Y J1518.7+0202   | SDSS J151640.21+00150 | 0.128                 | Lister16 | VLBA  | HERG        |
| FL8Y J1518.6+0613   | SDSS J151845.72+06135 | 0.1                   | Owen92 | VLA     | LERG        |
| FL8Y J1521.2+0421   | Parkes 1518+045 = CGCG 049-138 | 0.24               | Duncan93 | VLA     | LERG        |
| FL8Y J1631.0+8233   | NGC 6251        | 0.24                   | Pushkarev12 | VLA    | LERG        |
| FL8Y J1829.5+4846   | 3C 380          | 4.5                    | Yuan12 | VLA     | HERG        |
| FL8Y J1843.5-4835   | MRC 1839-487    | 0.16                   | Yuan12 | VLA     | LERG        |
| FL8Y J2004.1-3603   | MRC 1955-357    | < 0.21                 | Chherti13 | ATCA 20 GHz | HERG  |
| FL8Y J2329.7-2117   | MRC 2327-215    | < 0.1                  | Kapahi98 | VLA     | LERG        |

* See reference list for full references.
REFERENCES

Ackermann, M. et al. 2015, ApJ 799:86.

Ackermann, M. et al. 2016, Phys. Rev. Letters 116, 151105.

Ahnen, M.L. et al. 2017, A & A 603, 25A.

Akujor, C.E. et al. 1991, MNRAS 250, 215.

Atwood, W. et al., 2013, arXiv:1303.3514

Baldi, R.D., Capetti, A. & Massaro, F. 2018, A & A 609, A1.

Balmaverde, B. & Capetti, A. 2006, A & A 447, 97.

Best, P.N & Heckman, T.M., 2012a, Mon. Not. Royal Astr. Soc. 421, 1569.

Best, P.N. & Heckmann, T.M. 2012b, 2012yCat74211569.

Best, P.N. et al. 2014, Mon. Not. Royal Astr. Soc. 445, 955.

Bridle, A.H. & Vallee, J.P. 1981, AJ 86, 1165.

Bridle, A.H. et al. 1994, AJ 108, 766.

Chherti, R. et al. 2013, MNRAS 434, 956.

Condon, J.J. & Broderick, J.J. 1986, AJ 91, 1051.

Condon, J.J., Frayer, D.T. & Broderick, J.J. 1991, AJ 101, 362.

Di Mauro, M., Calore, F. Donato, F., Ajello, M. & Latronico 2014, L. ApJ 780:161.

Duncan, R.A. et al. 1993, PASAu 10, 310.

Falcke, H., Körding, E. & Nagar, N.M. 2004, New Astr. Rev. 48, 1157.
Fey, A.L., Clegg, A.W. & Fomalont, E.B. 1996, ApJS 105, 299.

Fernini, I. 2014, ApJS 212, 19.

Fomalont, E. B. et al. 1989, ApJ 346L, 17.

Grandi, P., Capetti, A. & Baldi, R.D. 2016, Mon. Not. Roy. Astr. Soc. 457, 2.

Hardcastle, M.J., Alexander, P., Pooley, G.G. & Riley, J.M. 1998, MNRAS 296, 445.

Herrera Ruiz, et al. 2017, A & A 607, A132.

Hooper, D., Linden, T. & Lopez, A., J. Cosmol. Astropart. Phys. 08 (2016) 019.

Inoue, Y. 2011, ApJ 733, 66.

Jones, D.L. & Wehrle, A.E. 1997, ApJ 484, 186.

Joshi, S.A., et al. 2011, MNRAS 414, 1397.

Kapahi, V.K. et al. 1998, ApJS 118, 275.

Kharb, P., Lister, M.L. and Cooper, N.J. 2010, ApJ 710, 764.

Kozieł-Wierzbowska, D. & Stasińska, G. 2011, MNRAS 415, 1013.

Lee, S.-S. et al. 2016, ApJ 826:135.

Lin, , Y.-T. et al. 2010, ApJ 723, 1119.

Lister, M.L. et al. 2016, AJ 152, 12.

Linden, T. 2017, Phys. Rev. D 96, 083001.

Liuzzo, E. et al. 2013, A & A 560, 23.

Mack, K.-H, Klein, U., O’Dea, C.P. and Willis, A.G. 1997, A&A Suppl. 123, 423.
Makiya, R., Totano, T. & Kobayashi, M. 2011, ApJ 728, 158.

Morganti, R. et al. 1997, MNRAS 284, 541.

Owen, F.N., White, R.A. & Burns, J.O. 1992, ApJS 80, 501.

Padovani, P. et al. 1993, MNRAS 260, L21.

Pushkarev, A.B. & Kovalev, Y.Y. 2012, A & A 544, 34A.

Pei, Z.-Y., et al. 2018, arXiv:1811.0877.

Saikia, D.J. 1999, MNRAS 302, L60.

Salamon, M.H. & Stecker, F.W. 1994, ApJ 430, L21.

Stecker, F.W. et al. 1993, ApJ 410, L71.

Stecker, F.W. & Venters, T.M. 2011, ApJ 736:40.

Stecker, F.W., Astropart. Phys. 26, 398.

Stecker, F.W., Scully, S.T. & Malkan, M.A. 2016, ApJ 827:6.

Tamborra, I., Ando, S. & Murase, K. 2014, J. Cosmol. Astropart. Phys. 09 (2014) 043.

An, T., Hong, X.-Y. & Wang, W.-H. 2004, ChJAA 4, 28.

Tingay, S.J. et al. 2003, PASJ 55, 351.

Unger, S. W., Booler, R.V. & Pedlar, A. 1984, MNRAS 207, 679.

van Velzen, S. 2015, MNRAS 446, 2985.

Vigotti, Gregorini, L. Klein, U. & Mack, K.-H. 1989, A&S 139, 359.

Yuan, Z. & Wang, J. 2012, ApJ 744, 84.
Yuan, Z., Wang, J. Worrall, D. et al. 2018, arXiv:1810.12713
Fig. 1.— Gamma-ray luminosities of radio galaxies from the Fermi FL8Y source list vs. estimated core radio luminosities at 5 GHz. All luminosities are given in $\text{erg/s}$. Blue circles denote LERGs and unclassified sources; green triangles denote HERGs. The red line is our fit (see eq. 1). Previous results derived using the earlier 3FGL Fermi catalog are also shown by dashed lines for comparison (Purple:Di Mauro et al. 2014, Yellow:Hooper et al. 2016).
Fig. 2.— Flux limited FR0 number-flux distribution from Baldi et al. (2018). The sample appears to become incomplete below $\sim 30$ mJy (see text). We also show our assumed Euclidean distribution extrapolated to 1 mJy.
Fig. 3.— Distribution of γ-ray spectral indexes for the 45 non-blazar radio loud AGN taken from the Fermi FL8Y compilation. The red dotted curve is the best fit Gaussian distribution with a mean value of 2.3 and a width of 0.35.
Fig. 4.— Radio galaxy core luminosity functions at 5 GHz derived from Yuan et. al. (2018) and used in our calculations as described in the text. The horizontal axis units are in $ergs/s$. 
Fig. 5.— Fermi measurements of the unresolved extragalactic γ-ray background (Ackermann et al. 2015) are shown in blue. Results of our calculation are shown by the red line and pink uncertainty band (see text). We find that $11 \pm 7\%$ of the unresolved EGB at $\sim 1$ GeV can be due to unresolved, core dominant radio galaxies.