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The Extragalactic Gamma-Ray Background from Core Dominated Radio Galaxies

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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 γ-rays to be detected individually by *Fermi*. Nevertheless, they may contribute significantly to the unresolved extragalactic γ-ray background. We consider here the possible contribution of these core dominated radio galaxies to the diffuse extragalactic γ-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 γ-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 γ-ray emitting radio galaxies to the unresolved extragalactic γ-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 γ-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 ~ 2.3 below ~ 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 γ-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 γ-rays at energies above 0.1 GeV, such γ-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 γ-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 γ-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 $> 4\sigma$.

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 [1] [2]. 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).[3] 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.[4] 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 γ-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 γ-ray emitting blazars such as BL Lac objects. In fact, it appears that *Fermi*-detected γ-ray emitting blazars are more core dominated than those not detected by *Fermi* (Pei et al. 2018).

We have updated the relation between γ-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 γ-ray luminosities to lower core radio luminosities.

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

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

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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 reprocessing, 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 an 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.[5]

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 $10^{22} - 10^{24}$

[5]Previous results were based on the smaller (3FGL) sample with about half the number of detections, and both incorporated upper limits in to 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} W/Hz. Because of their relatively low luminosity, they are expected to be extremely difficult to detect as individual γ-ray sources, as follows from relation (1)[6]. In fact, even at radio frequencies these galaxies have not been observed at redshifts above ~ 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 γ-ray background.

We have searched the literature as well as the Sloan Digital Sky Survey (SDSS) database for optical spectroscopy of the *Fermi*-detected radiogalaxies. The majority of them have an available optical spectrum which allows us to classify ∼93% of these radiogalaxies 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 ∼70% of them as LERGs and ∼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

[6]There has been one claimed detection of an FR0 designated as Toll 326-379 as a γ-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 $\geq F_r$ 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. [7]

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.

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[7]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.

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 γ-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 towards 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 reshift 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 γ-ray -loud radio galaxies are primarily LERGs.

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

We proceeded by deriving a γ-ray luminosity function based on our L_γ 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 γ-ray LF as

$$\Phi_\gamma(L_\gamma, z) = \Phi_R(L_R(L_\gamma), z) d\log L_R d\log L_\gamma, \tag{2}$$

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 γ-ray background from core dominated radio galaxies. We assume that these sources have γ-ray spectra of approximate power-law form $KE^{-\Gamma}$ in the energy range $0.1 < 100$ GeV. We assume a distribution of γ-ray spectral indexes, Γ, 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 γ-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 γ-ray luminosity function for core dominated radio galaxies. The γ-ray background is then given by

$$I(E_\gamma) = \int_{\Gamma_{min}}^{\Gamma_{max}} \frac{dn(\Gamma)}{d\Gamma} d\Gamma \int_0^{z_{\max}} dz \int_{L_{\gamma,\min}}^{L_{\gamma,\max}} \frac{dL_\gamma}{\ln(10) L_\gamma} \frac{d^2V}{d\Omega dz} \Phi_{\gamma,Core}(L_\gamma, z) \frac{dF_\gamma(L_\gamma, (1+z)E_\gamma, z)}{dE_\gamma} \, e^{-\tau(E_\gamma, z)} \tag{3}$$

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

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

7. Conclusions

Using radio maps we determined estimated core radio fluxes for the γ-ray emitting radio sources given in the expanded *Fermi* FL8Y source list. We used those results, to derive a new log-linear relation between γ-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 γ-ray luminosity range that corresponds to the range of radio galaxy core luminosities (in erg/s) $36.0 < \log L_\gamma < 45.0$ for γ-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 γ-ray emitters, the largest source of uncertainty in our calculation is the inherent scatter in the γ-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 ~ 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 ~ 100 GeV. In this regard, we note that the *Fermi* group has determined that $\sim 85\%$ of the unresolved γ-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 γ-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 γ-ray flux from core dominated radio galaxies can account for a minor, but non-negligible, $4\% - 18\%$ of the γ-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 γ-ray background can reasonably be accounted for.

Table 1. **Radiogalaxies Detected in 4FGL**

Fermi ID	Source ID	S_{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	Pks 0518-45 = 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 J0623.9-5300	MRC 0620-526	1.2	Chherti13	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	Kozeił11	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 J1219.5+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 J1306.7-2149	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_{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		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.

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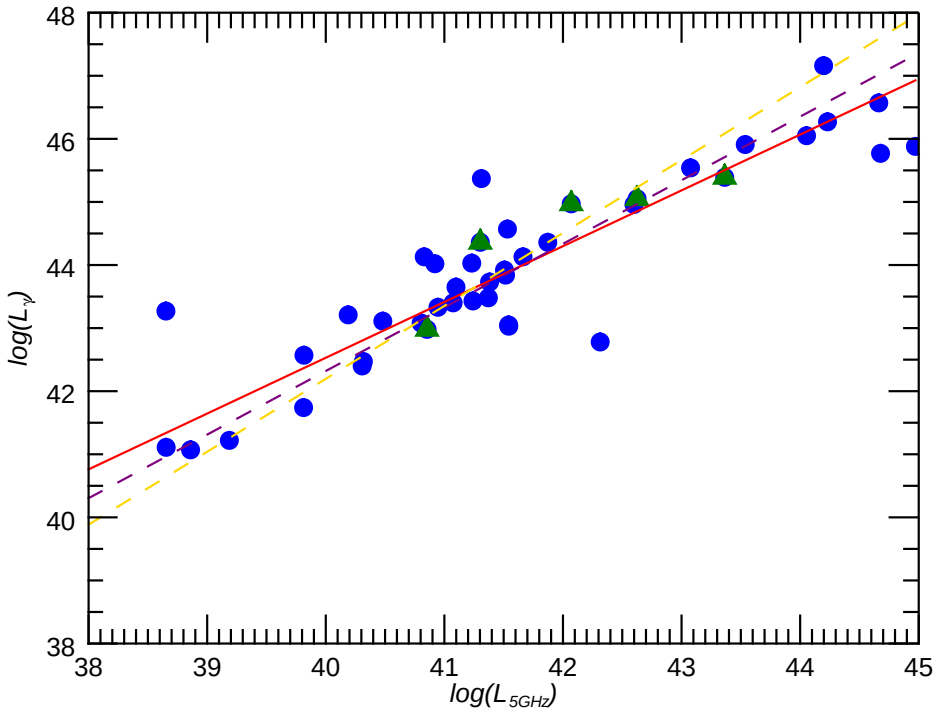

Fig. 1.— Gamma-ray luminosities of radio galaxies from the *Fermi* FL8Y source list vs. estimated core radio luminosities at 5 GHz. All luminosities are given in erg/s. Blue circles denote LERGs and unclassified sources; green triangles denote HERGs. The red line is our fit (see eq. (1). Previous results 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).

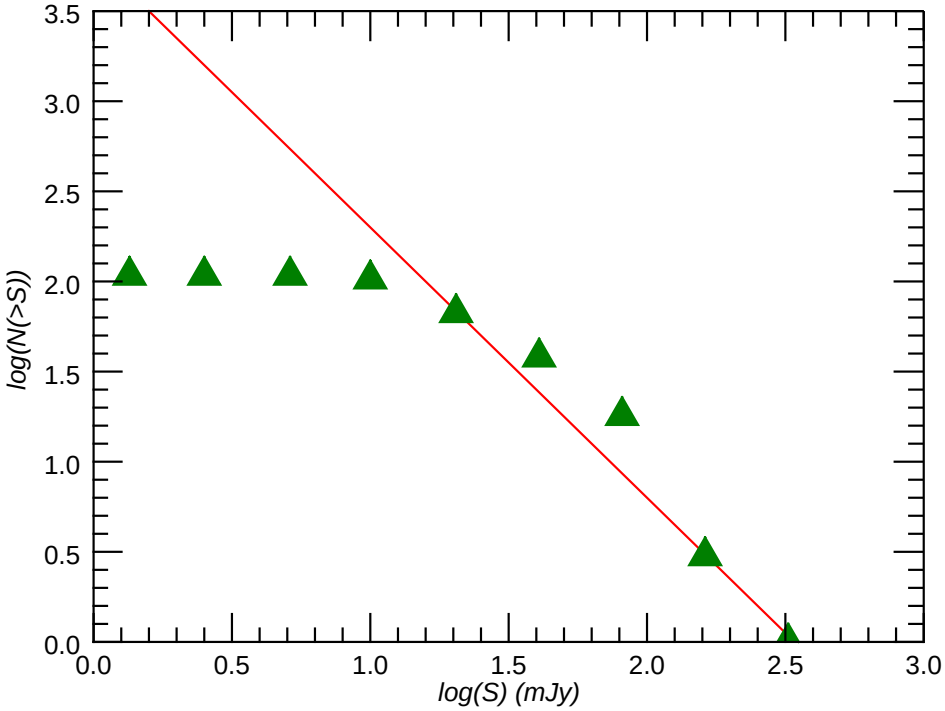

Fig. 2.— Flux limited FR0 number-flux distribution from Baldi et al.(2018). The sample appears to become incomplete below $\sim$ 30 mJy (see text). We also show our assumed Euclidean distribution extrapolated to 1 mJy.

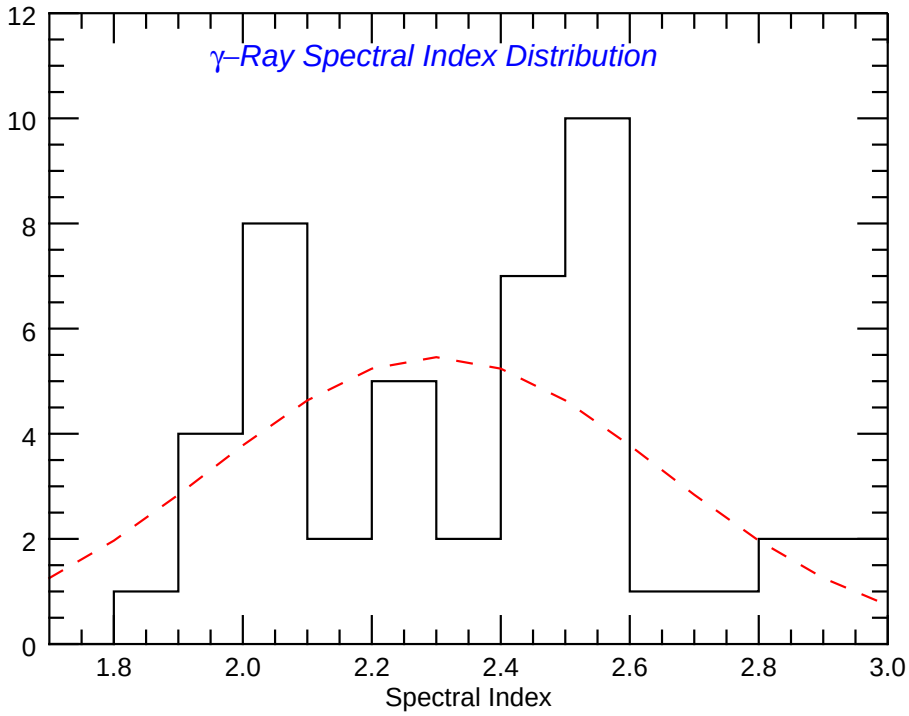

Fig. 3.— Distribution of γ-ray spectral indexes for the 45 non-blazar radio loud AGN taken from the *Fermi* FL8Y compilation. The red dotted curve is the best fit Gaussian distribution with a mean value of 2.3 and a width of 0.35.

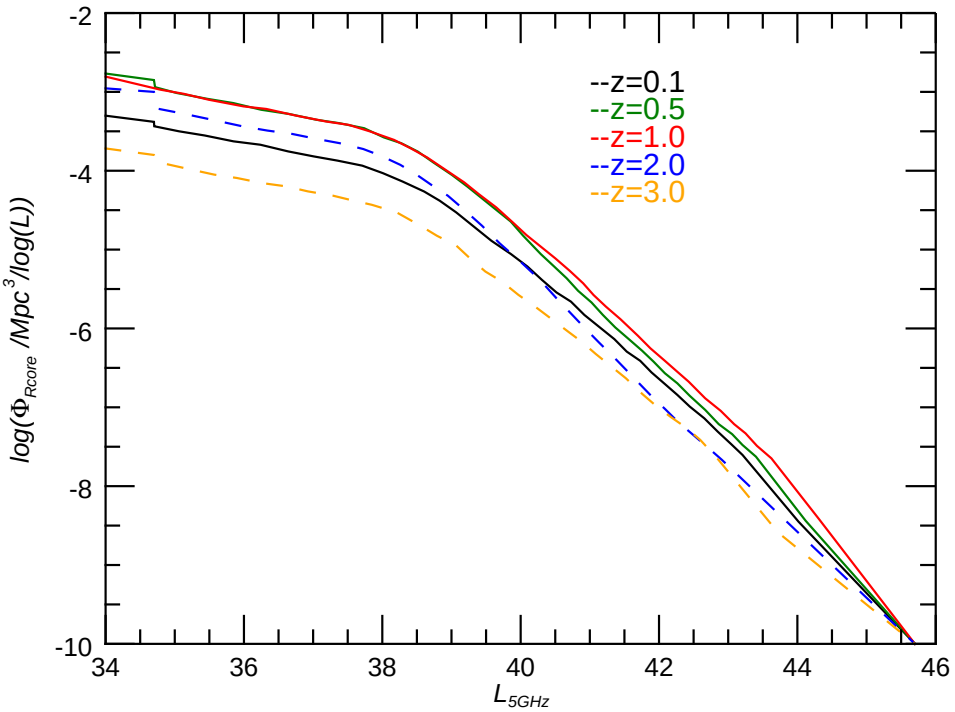

Fig. 4.— Radio galaxy core luminosity functions at 5 GHz derived from Yuan et. al. (2018) and used in our calculations as described in the text. The horizontal axis units are in $ergs/s$.

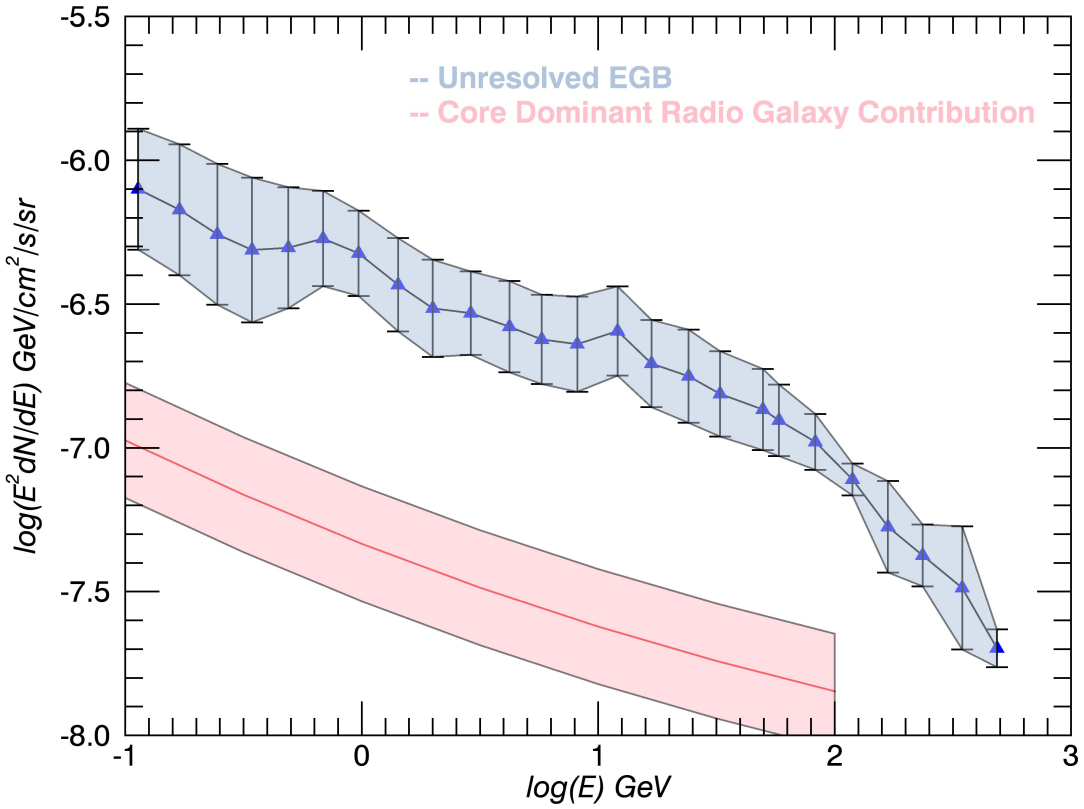

Fig. 5.— Fermi measurements of the unresolved extragalactic γ-ray background (Ackermann et al. 2015) are shown in blue. Results of our calculation are shown by the red line and pink uncertainty band (see text). We find that $11 \pm 7\%$ of the unresolved EGB at ~ 1 GeV can be due to unresolved, core dominant radio galaxies.