# The Blazar Gamma-Ray Luminosity Function and the Diffuse Extragalactic Gamma-Ray Background

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## Abstract

We have used the data from the new EGRET catalogue on "grazars" (blazars which are observed to be high energy $\gamma$-ray sources), together with radio data, to construct a new relation between radio and $\gamma$-ray luminosity for these sources. Using this relation to construct a grazar $\gamma$-ray luminosity function, we then calculate the contribution of unresolved grazars to the cosmic $\gamma$-ray background radiation. We derive the energy spectrum of this background component above 100 MeV and the angular fluctuations in this background implied by our model.



*Subject headings:* gamma-rays: theory – galaxies: active – quasars: general

## 1. Introduction

The EGRET team has discovered that there is a class of objects which are very strong, and probably highly time variable $\gamma$-ray emitters. These are the flat spectrum radio quasars (FSRQ) optically violent variable (OVV) quasars and BL Lac objects, which together have been classed as "blazars". These objects generally have superluminal jets with the jets beaming their emission toward us. It is natural to assume that, since the jets are optically thin to high energy $\gamma$-rays and since beaming in relativistic jets can produce a large enhancement in the apparent $\gamma$-ray emission relative to unbeamed compoents, therefore, the $\gamma$-ray emission from these objects is probably beamed and originates in the jets. This hypothesis is supported by the rapid $\gamma$-ray time variability observed for 3C279 (Kniffen, *et al.*1992). The EGRET team has most recently reported the solid detection of 25 blazars and the marginal detection of 13 more (Fichtel, *et al.*1994). All of these $\gamma$-ray sources, which we hereafter refer to as "grazars", are also flat spectrum radio sources in the 2 to 5 GHz band. We will use this empirical fact to attempt to construct the grazar $\gamma$-ray luminosity function. From that determination, we will then calculate the unresolved blazar contribution to the high-energy (>100 MeV) cosmic $\gamma$-ray background radiation and the angular fluctuations expected for this component of background radiation.

## 2. Flat Spectrum Radio Quasars and Grazars

The 38 grazars mentioned above have fluxes at or above $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which roughly corresponds to the average EGRET survey sensivity limit. All these grazars are contained within the blazar population, yet they constitute only a minority of flat spectrum radio

sources, even at the higher radio luminosities where almost all of the EGRET observed grazars are seen to lie. At least another 135 radio-bright FSRQs (Dunlop and Peacock 1990) were within the field-of-view of the full sky EGRET telescope survey. Those sources have not been seen as grazars above the survey flux sensitivity level. If we maintain the assumption that all blazars are likely grazars, there are a few explanations for the paucity of EGRET sources within our potential population. One possibility is that the opening angle of the beamed $\gamma$-rays is smaller than that of radio photons, so that only a fraction of the blazars can be detected in $\gamma$-rays . Another is that the $\gamma$-ray emission is somehow "turned-on" in all sources only a fraction of the time. A third hypothesis is that all blazars are also grazars, but that the EGRET flux sensitivity has so far limited us to observing only those sources in the high-luminosity wing of whatever distribution relates the radio and $\gamma$-ray luminosities. Lastly, for some unknown reason, only a small subset of blazars may be grazars.

We will make the basic assumption that grazars are FSRQ's, with fewer potential $\gamma$-ray sources being seen because the $\gamma$-ray beaming angle $\theta_\gamma$ is smaller than the radio beaming angle width $\theta_r$. We therefore implicitly assume that the radio and $\gamma$-ray emission have, on average, the same duty cycle. An attractive aspect of this assumption is that it is within the spirit of the "unified" AGN models which attempt to account for the various classes of AGN as aspects of one basic astronomical object (*e.g.*Padovani and Urry 1992). The solid angle ratio $(\theta_\gamma/\theta_r)^2 < 1$ then becomes a parameter for testing the model against theoretical considerations, as we discuss later. With the additional assumption that the differential $\gamma$-ray source luminosity (per steradian) $P_{\gamma f} \equiv P_\gamma(E_{\gamma f})$, evaluated at the fiducial $\gamma$-ray energy

$E_{\gamma f} = 100$ MeV, scales with the differential radio source luminosity $P_{rf}$, evaluated at the fiducial radio energy $E_{rf} = 2.7$ GHz, the $\gamma$-ray luminosity function (GLF) $\rho_\gamma(P_{\gamma f}, z)$ is then derived from the radio luminosity function (RLF) $\rho_r(P_{rf}, z)$ by simple scaling relations.

## 2. The Gamma Ray Luminosity Function $\rho_\gamma(P_\gamma, z)$

For our analysis we use the FSRQ luminosity function of Dunlop and Peacock (1990),

$$\rho_r(P_{rf}, z) = 10^{-8.15} \left[ \left( \frac{P_{rf}}{P_c(z)} \right)^{0.83} + \left( \frac{P_{rf}}{P_c(z)} \right)^{1.96} \right]^{-1}, \qquad [1]$$

where $\log_{10} P_c(z) = 25.26 + 1.18z - 0.28z^2$, and the units of luminosity $P_r$ ($P_\gamma$) and co-moving density $\rho_r$ ($\rho_\gamma$) are respectively W/Hz-sr and Mpc$^{-3}$-(unit interval of $\log_{10} P)^{-1}$. This RLF corresponds to pure luminosity evolution with $\Omega_0 = 1$ and $H_0$ taken to be 50 km/s-Mpc.

¿From the RLF one can calculate the expected observed distribution $n_{obs}(P_{rf})$ of FSRQ sources for a survey with a given flux sensitivity $S_{r,min}$. For a source with spectral index $\alpha_r$, where $P_r = P_{rf}(E_r/E_{rf})^{-\alpha_r}$, the observed flux density at the fiducial energy $E_{r,f}$ is given by

$$S_r(E_{rf}) = P_{rf} / \left[ r^2 R_0^2 (1+z)^{\alpha_r + 1} \right], \qquad [2]$$

where $r$ is the co-moving coordinate of the source, and $R_0$ is the present cosmological scale factor. For a given source luminosity $P_{rf}$, the maximum detectable distance $R_0 r_{max}$ is found by subsituting $S_{r,min}$ for $S_r$ in Eq. 2. The total number of sources of luminosity $P_{rf}$ seen at Earth is then

$$n_{obs}(P_{rf}) d(\log_{10} P_{rf}) = \int_0^{R_0 r_{max}} 4\pi R_0^3 r^2 \rho_r(P_{rf}, z)\, dr\, d(\log_{10} P_{rf}). \qquad [3]$$

For $\Omega_0 = 1$ and $\Lambda = 0$, $R_0 r = (2c/H_0)\left[1-(1+z)^{-1/2}\right]$. Expression [3] then becomes an integral over redshift. For any given $P_{rf}$, the upper limit of this integral is $\min(z_{max}, 5.0)$, where AGN formation is assumed to take place at $z = 5.0$. We have checked that eqs.[1]-[3] predict a grazar redshift distribution which is consistent with the EGRET observations.

Figure 1 shows the results of a full-sky survey (9.81 sr) at 2.7 GHz, with a sensitivity of 2 Jy (Wall and Peacock, 1985). The absolute magnitudes $P_{rf}$ of these FSRQ's are calculated using the measured (or estimated) redshifts listed by Wall and Peacock (1985). A mean spectral index of $\langle\alpha_r\rangle = 0$ is assumed for spectral extrapolations, to be consistent with the value used by Dunlop and Peacock (1990) in the determination of their FSRQ RLF (Eq. 1). Also shown in Figure 1 is the expected distribution $n_{obs}(P_{rf})$, calculated using Eq. 3 for a radio flux sensitivity $S_{r,min} = 2$ Jy, and scaled to correspond to a 9.81 sr survey. The fit is consistent with the quality of fit specified by Dunlop and Peacock (1990) for their RLFs, *i.e.* better than 1%, and shows that the general features of the measured $P_{rf}$ distribution are indeed reproduced with Eq. 3.

By assumption, a grazar's $\gamma$-ray luminosity scales with its radio luminosity, $P_{\gamma f} = 10^{\xi} P_{rf}$. The parameter $\xi$ is estimated from the distribution of ratios of measured $\gamma$-ray and radio fluxes of the EGRET grazars. For those EGRET sources with unknown redshifts or spectral indices, values of $z = 1$ and $\alpha_\gamma = 1$ were assumed for the calculation of the spectral correction factor (see Eq. 2). Radio fluxes at 2.7 GHz were obtained from Wall and Peacock (1985), Kühr *et al.*(1981), Becker *et al.*(1991), and Ledden and O'Dell (1985). Figure 2 shows the EGRET sources' radio and $\gamma$-ray luminosities; from these data we obtain a mean $\xi = -9.8$, with $\sigma_\xi = 0.6$.

For a fixed $\xi$, the GLF is given by

$$\rho_\gamma(P_{\gamma f}, z) = (\theta_\gamma/\theta_r)^2 \rho_r(P_{\gamma f}/10^\xi, z). \qquad [4]$$

The normalization factor $(\theta_\gamma/\theta_r)^2$ is determined by the requirement that the calculated total number of $\gamma$-ray sources above the EGRET threshold match the number seen by EGRET (38 sources), giving $(\theta_\gamma/\theta_r)^2 = 0.071(0.011, 0.56)$ for $\xi = -9.8(-9.2, -10.4)$. Our model assumptions then lead to the conclusion that because the $\gamma$-ray beam width is smaller than the radio beam width, only a fraction of the observed blazars will be seen to be grazars as well. Recent estimates of the radio beam width, $\sim 14°$ (Padovani and Urry, 1992), imply a $\gamma$-ray beam width of $\sim 4°(2°, 10°)$.

The GLF obtained above is used in Eq. 3 to calculate the *expected* $\gamma$-ray luminosity distribution of *observed* sources, shown in Figure 3. Also shown in this figure is the distribution of source luminosities $P_{\gamma f}$ for the 33 EGRET sources which have an identified redshift. These luminosities have been calculated using the measured spectral index $\alpha_\gamma$ of each source; for sources of unknown index, a mean value $\langle \alpha_\gamma \rangle = 1.0$ is assumed. It is apparent from this figure that somewhat higher values of $\xi$ than our mean give a better fit to the observations, with $\xi = -9.2$ providing a reasonable (better than 5%) fit.

## 3. The Gamma-Ray Background (GRB)

Given the GLF for a chosen value of $\xi$, the contribution of direct $\gamma$-ray beaming from blazars to the $\gamma$-ray background (GRB) can be calculated. The differential number flux $\phi_\gamma^{(1)}(E_0)$ at observed energy $E_0$ from a single source of luminosity $P_{\gamma f} = P_\gamma(E_{\gamma f})$ at

redshift $z$ is given by

$$\phi_\gamma^{(1)}(E_0) = \frac{H_0^2 P_{\gamma f}(E_0/E_{\gamma f})^{-(\alpha_\gamma+1)}}{4c^2 E_{\gamma f}(1+z)^{\alpha_\gamma+1}\left[1-(1+z)^{-1/2}\right]^2}, \qquad [5]$$

where the minor effect of $\gamma$-ray extinction off the infrared background (Stecker, DeJager, and Salamon, 1992; Stecker, Salamon and Malkan 1993) is neglected for our energy region of interest, 0.1 to 100 GeV. The total differential number flux $\phi_\gamma$ is then given by

$$\begin{aligned}\phi_\gamma(E_0) = &\frac{c}{H_0 E_{\gamma f}\ln 10}\sum_i p(\alpha_i)\left(\frac{E_0}{E_{\gamma f}}\right)^{-(\alpha_i+1)} \times \\ &\int_{z_{min}(P_{\gamma f})}^{5} \frac{dz}{(1+z)^{\alpha_i+5/2}} \int_{P_{min}}^{P_{max}} dP_{\gamma f}\, \rho_\gamma(P_{\gamma f}, z),\end{aligned} \qquad [6]$$

where $P_{min}$ and $P_{max}$ are fixed by the radio luminosity limits in the RLF of Dunlop and Peacock (1985), *viz.*, $P_{r,min} = 10^{18}$ W/Hz-sr and $P_{r,max} = 10^{30}$ W/Hz-sr. Because this component of the diffuse GRB is due to ***unresolved*** grazars, a lower limit on redshift, $z_{min}(P_{\gamma f})$, eliminates sources above the source detection threshold. The summation is over the probability distribution $p(\alpha_\gamma)$ of $\gamma$-ray spectral index, taken from the EGRET data.

For the values $\xi = (-9.2, -9.8, -10.4)$ we obtain GRB differential fluxes that are well approximated (to within 10%) by $\phi_\gamma(E_0) = (2.3, 4.3, 9.1) \times 10^{-7}(E_0/1\ \text{GeV})^{-2.0}$ $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$. (Our calculated spectrum is actually slightly softer at lower energies and slightly harder at higher energies, owing to the spread in observed grazar spectral indices about a mode of 2.0, given by $p(\alpha_\gamma)$.)

## 4. Angular Fluctuations

Poisson fluctuations in the number of unresolved blazars contained within a field-of-view (FOV) will contribute to variations in the integrated GRB flux over angular position in the sky. With the GLF given above, one can predict the rms fluctuation in the integrated GRB flux that should be observed as a function of instrument sensitivity. Also contributing to the observed variations will be fluctuations due to photon statistics, but with a large enough detector area$\times$time factor, $At$, these can be made negligible.

We start by dividing $P_{\gamma f} \otimes z$ space into cells, $[P_{\gamma f}, P_{\gamma f} + dP_{\gamma f}] \otimes [z, z + dz]$. Neglecting photon statistics, the mean photon flux (>100 MeV) incident on a detector from each cell is $\langle r_i \rangle = \eta_i \mu_i$, where the number of sources within a FOV of unit solid angle is Poisson-distributed about a mean value $\eta_i$, and $\mu_i$ is the mean photon flux from a single source within that cell. Integrating over all cells, the total mean photon flux is $\langle R \rangle = \sum \eta_i \mu_i$. A straightforward statistical calculation shows that the variance in the total flux is $\sigma_R^2 = \sum \eta_i \mu_i^2$. For a detector of effective area$\times$time $At$ and solid angle $\Omega$, the mean photon *count* from a single source scales with $At$, while the mean number of sources within a cell scales as $\Omega$, so that the mean total photon count $\langle N \rangle = At\Omega \langle R \rangle$. The condition that fluctuations due to photon statistics are negligible compared to fluctuations in source counts within a FOV is given by $\langle N \rangle \ll \sigma_N^2 = \sum (\Omega \eta_i)(At\mu_i)^2$, or equivalently, $At \gg \langle R \rangle / \sigma_R^2$.

Using the GLF to determine $\eta_i$ for each cell, we find that $\langle R \rangle \approx 4 \times 10^{-6} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$ and $\sigma_R \approx 2 \times 10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$, so that $At$ must be $\gg 10^8 \mathrm{cm}^2 \mathrm{s}$ to see actual source count fluctuations rather than photon statistics. The EGRET detector has an area of 1500 $\mathrm{cm}^2$, a typical viewing period of 2 weeks, and an effective duty cycle of $\sim$ 30 % ,

giving $At \sim 6 \times 10^8 \mathrm{cm}^2\mathrm{s}$, thereby meeting this criterion. If the high galactic latitude diffuse galactic forground radiation, whose fluctuations are expected to be roughly proportional to the HI column density fluctuations, can be subtracted out, our predicted extragalactic fluctuations from grazars should be observable as a test of our model.

## 5. Discussion of Results

The key to an understanding of the origin of the cosmic $\gamma$-ray background may lie in the realization that it may well be composed of a number of different components having different origins and that these components in turn may dominate the GRB only in specific energy ranges. For example, a possible matter-antimatter annihilation component (Stecker 1985) will only be important in the energy range between $\sim$ 1 MeV and $\sim$ 1 GeV. The active galaxy source models must also be broken up by energy range. It is now known that Seyfert galaxies typically have spectra which drop off sharply above $\sim$ 0.1 MeV (Cameron, *et al.*, 1993) and that no Seyfert galaxies have been detected by EGRET at energies in the 100 MeV range (Lin, *et al.*, 1993). Therefore, they are not good candidates for explaining the high energy GRB. The generally accepted reason for this is that the photon fields in active galactic nucleii (AGN) are so intense that pair production prevents the higher energy $\gamma$-radiation from escaping (Svensson 1986; Zdziarski 1986; Done and Fabian 1989). Thus, although radio-quiet AGN may provide a substantial contribution to the X-ray background, and may also provide the dominant contribution to the high energy neutrino background (Stecker, Done, Salamon and Sommers 1991; 1992), these objects are not expected to be important sources of high energy $\gamma$-radiation. We have shown here that

blazars, or their subset grazars, can provide a substantial component to the high energy $\gamma$-ray background in the GeV energy range and above. In addition, our present method of calculating the $\gamma$-ray background from blazars has two advantages over the previous method of Stecker,*et al.*(1993) in that (1) the model involves some physical parameters such as beaming angle and duty cycle which allows us to relate the data to the theoretical emission process, and (2) the present model allows us to predict angular fluctuations for the background radiation.

For the set of observed grazars, we find that there is a mean ratio of $\gamma$-ray -to-radio luminosity of $10^{-9.8}$ with a 1 $\sigma$ error of $\pm 0.6$ in the exponent. Assuming the entire set of FSRQs defined by Dunlop and Peacock to be grazars and using their luminosity and redshift distributions together with the empirically determined range of values for $\xi$ and an EGRET sensitivity threshhold of $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, we predict the observed grazar luminosity distribution to be given by the curves shown in Fig. 3, which are consistent with the histogram of observed grazars also shown in that figure, provided a normalization factor is used to define the fraction of FSRQs which are observed as grazars at a given time. Under the assumption that this normalization factor is due entirely to a difference in the opening angles between the $\gamma$-ray jet and the radio jet, we find $(\theta_\gamma/\theta_r)^2 = \mathcal{O}(10^{-2}\ to\ 10^{-1})$ which would imply that the $\gamma$-ray emission is more highly collimated than the radio emission in the jet. This, in turn, would appear to favor a hadronic (relativistic proton) origin for the high-energy $\gamma$-ray emission since electron-origin unified AGN jet models would predict both the $\gamma$-ray and X-ray emission to be much more spread out with an opening angle considerable wider than that for the radio emission (Ghisellini, *et al.*1992). In contrast, the

opening-angle interpretation for the grazar data would appear to require a rather narrow ($\sim 4°$) accelerated beam of relativistic protons to coexist with the electrons accelerated in the jet and produce the high-energy $\gamma$-ray emission. Other possibilities for interpreting our results would be to posulate that (1) for some reason $\gamma$-ray emission is produced much less frequently in a grazar than radio emission or (2) that grazars represent a small subset of blazars. The choice of interpretation does not affect our calculation of the $\gamma$-ray background spectrum since our derived GLF is independent of its explanation.

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## Figure Captions

**Figure 1:** Radio luminosity distribution of *observed* FSRQs at 2.7 GHz. Filled circles correspond to the 2 Jy full-sky (9.81 sr) survey of Wall and Peacock (1985), where absolute luminosities have been calculated as described in the text. The asterisks show the expected luminosity distribution from Eq. 4, where we have used 2 Jy as the radio flux sensitivity at 2.7 GHz, and have assumed a 9.81 sr sky coverage. The calculated curve has not been normalized; the integrated number of expected FSRQ sources from Eq. 4 (=89) should in principle be equal to the number of FSRQs from the Wall and Peacock (1985) survey (=69).

**Figure 2:** Scatter plot of radio (2.7 GHz) and $\gamma$-ray (100 MeV) luminosities for the 38 EGRET sources. Sources of unknown redshift are assumed to have $z = 1.00$ for the calculation of the spectral correction factors (Eq. 3), required to obtain absolute luminosities from measured fluxes. The lines represent the relation between the radio and $\gamma$-ray luminosities, $P_{\gamma f} = 10^{\xi} P_{rf}$. The solid line corresponds to $\xi = -9.8$, while the dashed and dotted lines respectively correspond to $\xi = -9.2$ and $\xi = -10.4$.

**Figure 3:** $\gamma$-ray luminosity distribution of *observed* FSRQs at 100 MeV. This Figure is the $\gamma$-ray analog of Figure 1; here the EGRET source luminosities are histogrammed. (EGRET sources of unknown redshift have been excluded from this plot.) Also plotted are the results of applying Eq. 4 to the GLF, determined from Eq. 5 for a given value of $\xi$. Unlike the calculated radio luminosity distribution of Figure 1, these three curves (for $\xi$ = -9.2, -9.8, -10.4) *are* normalized so that the integrated number of expected sources

matches that observed. It is this normalization factor that gives the ratio of the radio and $\gamma$-ray beaming angles in this model. The $\xi = -9.2$ curve fits the observed distribution with a confidence level of 6%, with poorer fits for the other two $\xi$ values.

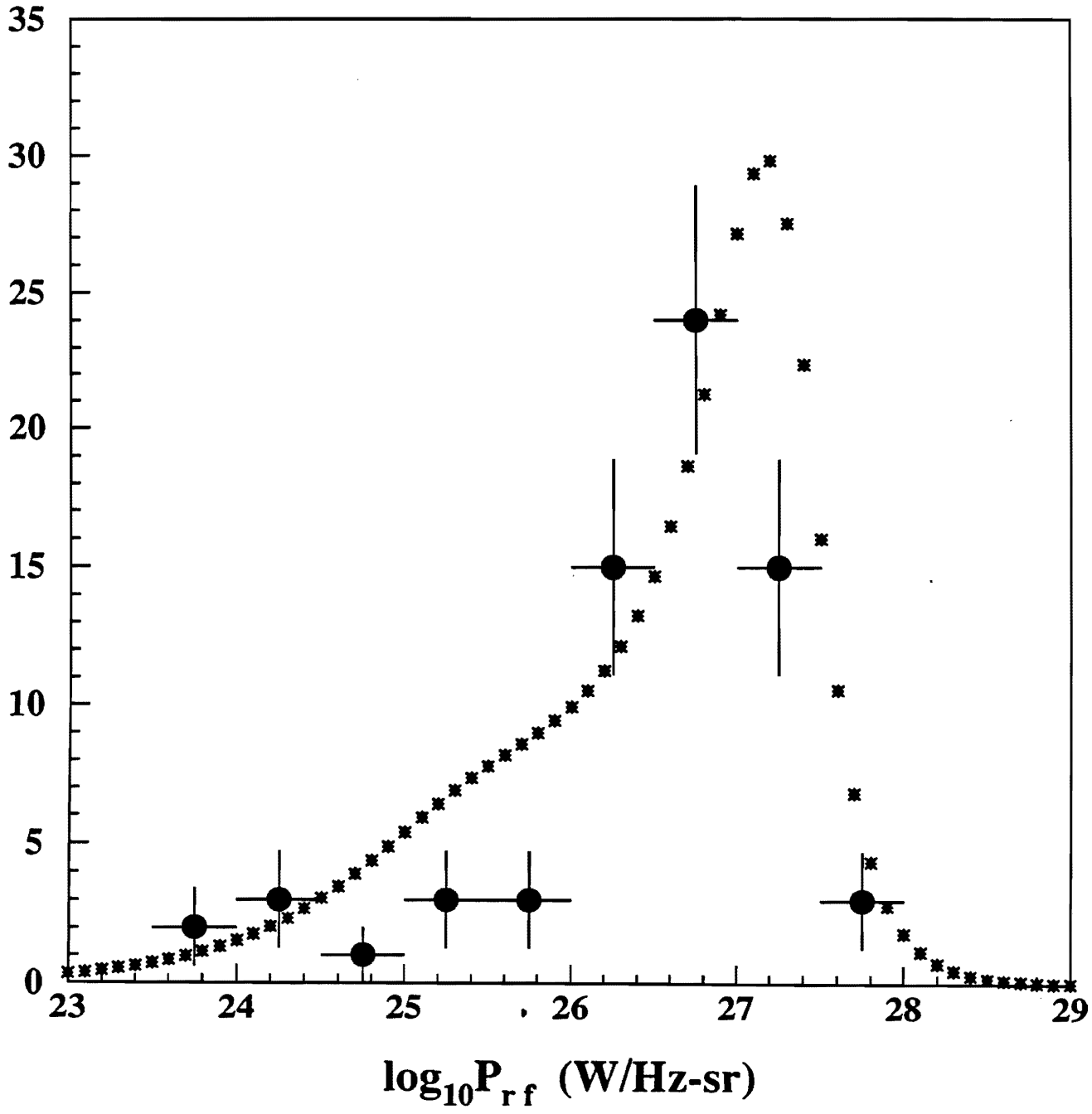
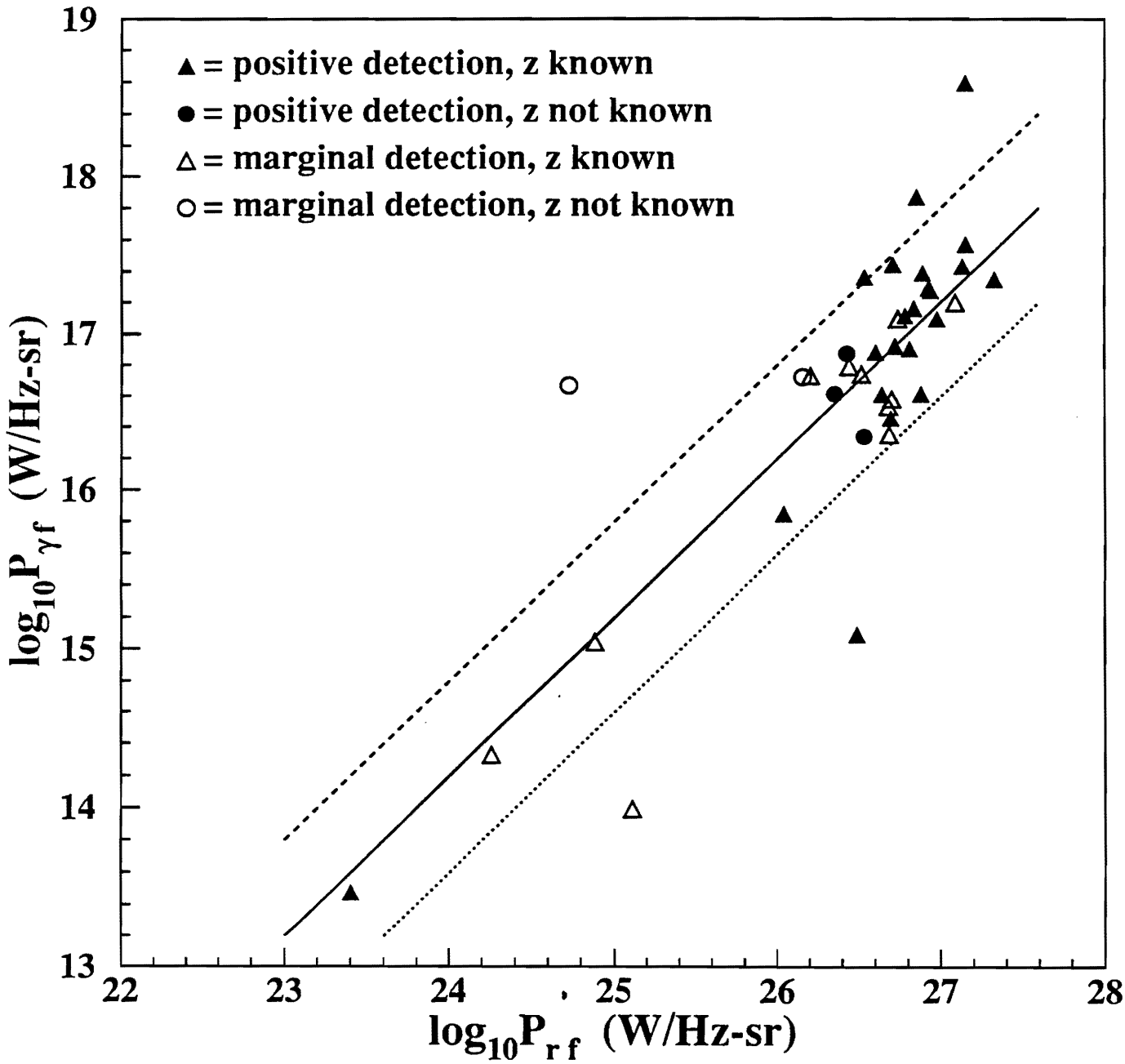



Figure 1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$\log_{10}P_{\gamma f}$ (W/Hz-sr)
$\log_{10}P_{rf}$ (W/Hz-sr)

Figure 2

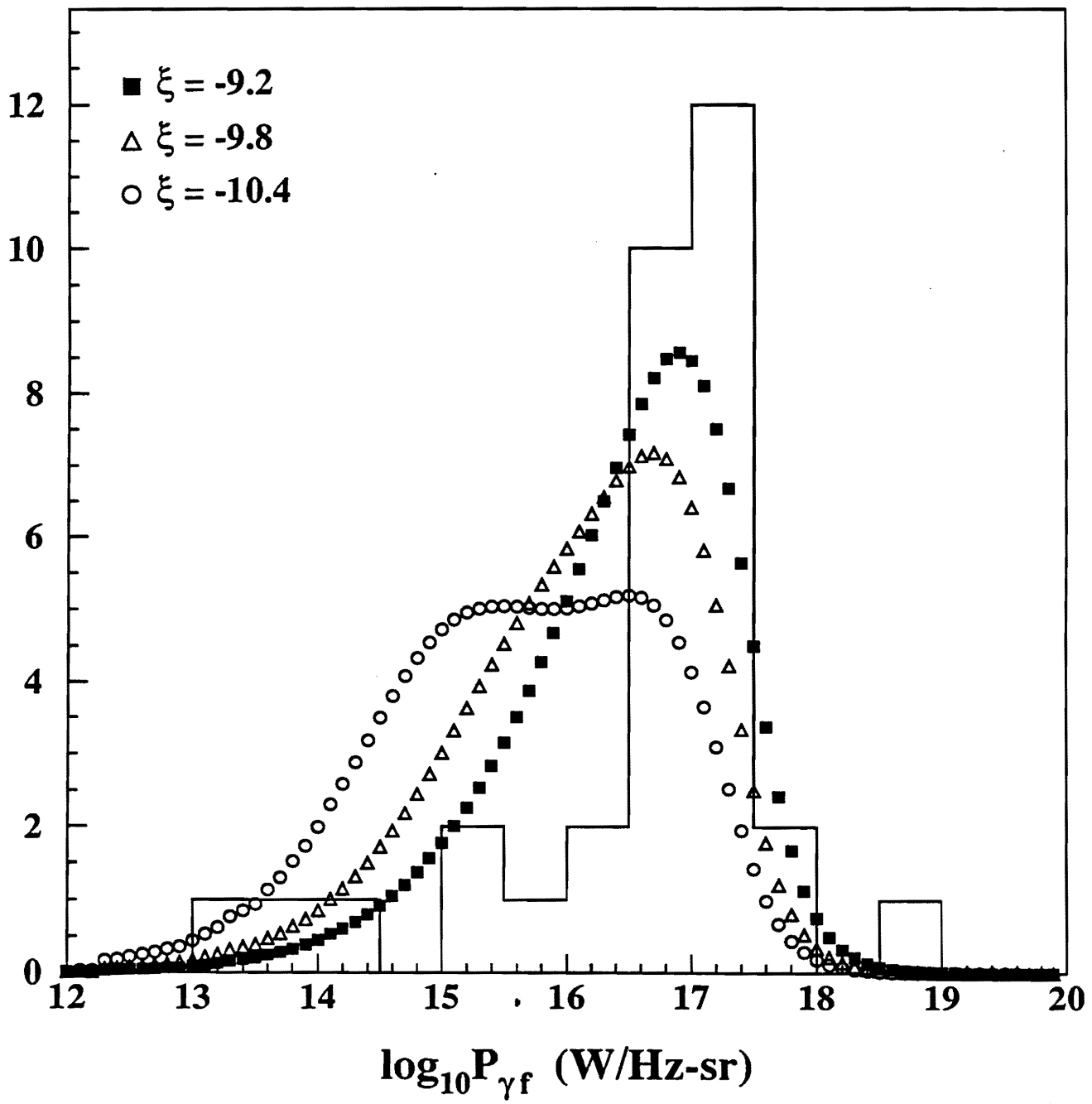
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Figure 3