# MILAGRO Source Counts: Estimating the Number of Detectable XBLs

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## 1 Introduction

Recently, I have been thinking about the number of sources that we (Milagro) might expect to detect during the next few years. Detection of additional extragalactic sources, in addition to being an experimental triumph, may allow us to set limits (or detect) the cosmic infrared background and study the nature of $\gamma$-ray production mechanism(s). Specifically, I wanted to estimate potential source counts by extrapolating from detections at lower energies. Putting aside for a moment any unknown objects that may be detected, or additional serendipitous help from nature (ie. GRBs, PBHs, WIMPS, etc.), these extrapolations may be the most realisitic estimates for the number of sources we expect to detect with Milagro - they are certainly the most conservative. To my knowledge there have not been any previous source count estimates made for Milagro.

It is true, of course, that we are probing a relatively unsampled astronomical energy regime and the argument can (and will) be made that *a priori* source count estimates are not relevant. In my view this is only partially true; one can make some estimates based on *reasonable* assumptions, and this is my goal here. In this memo I will address only one class of potential sources: X-ray selected BL Lacs (XBLs).

## 2 XBL Review

Nearby BL Lac objects are the only detected (and confirmed) extragalactic TeV $\gamma$-ray sources. The multiwavelength spectrum of BL Lacs, and AGN in general, show a characteristic double hump in the $\nu F_\nu$ plots (see, for example, Figure ??). The most popular explanation is that the synchrotron emission from relativistic electrons produces the low energy bump, while inverse Compton scattering is responsible for the feature at higher energies. It is unclear whether the high energy emission is due to Compton upscattering of the synchrotron photons themselves or some other low energy emission from, say, an accretion disk. To date, three sources - Mkn421 ($z = 0.031$), Mkn501 ($z = 0.034$), and 1ES2344+514 ($z = 0.044$)[1] - have been detected. All three objects are observed to have both quiescent and flaring states, and all are XBLs.

The definition of an XBL is somewhat arbitrary. Typically, BL Lacs classified based on the ratio of the source flux at X-ray and radio energies, $log(F_x/F_r)$. The *EINSTEIN* Slew Survey [1] classifies BL Lac objects as follows:

$$log(F_x/F_r) \left\{ \begin{array}{ll} \geq 5.5 & \mathrm{X-ray\,selected\,BL\,Lacs\,(XBLs)} \\ < 5.5 & \mathrm{radio\,selected\,BL\,Lacs\,(RBLs)} \end{array} \right. \qquad (1)$$

For most of the BL Lac objects detected by EGRET above 100 MeV, the "synchrotron" feature appears to peak at energies somewhere between radio and optical. In contrast, the $\nu F_\nu$ spectrum of the TeV emitting BL Lacs appears shifted to higher energies with the "synchrotron" emission peaking at a few keV. The consequence here is that if the inverse Compton process is truly responsible for the high energy emission, then the X-ray bright objects may represent the most promising TeV candidates. As mentioned above, only XBLs have been detected at TeV energies. It is interesting to note that the RBL with the hardest GeV spectrum, ON231, has not been seen at higher energies [2]; of course, it is difficult to know whether this is due to the $\gamma$-ray production mechanism or because of the object's distance ($z = 0.1$). Anyway, the purpose here is not to detail individual models.

## 3 Technique

Let us assume that the Synchrotron Self-Compton (SSC) model describes the spectral shape of these objects; it has been shown by a number of authors that a relatively simple SSC model can indeed parameterize the

[1] 1ES2344+514, initially detected by the Whipple Collaboration has not been independently confirmed

spectrum well. If I assume that inverse Compton upscattering of the X-ray emission generates the TeV emission then it is possible to get a proportionality between $\nu_X F_X$ and $\nu_{TeV} F_{TeV}$. In its $\gamma$-ray quiet state, Mkn421 appears to have roughly equal power at X-ray and TeV energies [3]; Mkn501 on the other hand has slightly less power (about a factor of 2-3) at TeV than and X-ray energies [4]. In order to err on the optimistic side, for the remainder of this memo I will assume the relationship is given by:

$$\nu_X F_X = \nu_{TeV} F_{TeV} \tag{2}$$

It is now possible to estimate the number of sources observable at TeV energies. I have used the *EINSTEIN* Slew Survey sample to compile a list of XBLs using the selection criteria defined above (Equation 1). This catalog quotes the X-ray source flux at 2 keV in $\mu$Jy. To convert to useful units I use the conversion factors

$$1\,\mu\mathrm{Jy} = 1.509 \times 10^{-3}\,\mathrm{keV\,cm^{-2}\,s^{-1}\,keV^{-1}},$$

$$\nu(2\,\mathrm{keV}) = 4.84 \times 10^{17}\,\mathrm{Hz},$$

$$\nu(300\,\mathrm{GeV}) = 7.26 \times 10^{25}\,\mathrm{Hz},$$

and the power spectrum proportionality from Equation 2 to get:

$$F_{300\,\mathrm{GeV}} = \left(\frac{F_X}{\mu\mathrm{Jy}}\right) \cdot 2.01 \times 10^{-11}\,\mathrm{keV\,cm^{-2}\,s^{-1}} \tag{3}$$

where, $F_X$ is measured in $\mu$Jy. If I assume that above 300 GeV, BL Lacs have an energy spectrum with $\alpha = 2$ (ie. $E^{-2}$), then after integrating the flux given above and normalizing to the observed integral flux from Mkn421 above 300 GeV [5] I end up with

$$I(\geq 300\,\mathrm{GeV}) = \left(\frac{F_X}{\mu\mathrm{Jy}}\right) \cdot 2.48 \times 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}} \tag{4}$$

# 4 Source Counts

Now that I have an equation for the integral TeV flux as a function of the X-ray flux I am almost ready to estimate the number of observable XBLs. The remaining piece of information is the sensitivity of our detector. For the purpose of this memo I will assume that Milagro's sensitivity is $I(\geq 300\,\mathrm{GeV}) = 1 \times 10^{-10}\,\mathrm{cm^{-2}\,s^{-1}}$. This is roughly a factor of 3 improvement over what the existing Monte Carlo and reconstruction code predict ($\approx 5\sigma$ on the Crab per year) and is, therefore, optimistic based on the current state-of-the-art. I will further assume that the flux sensitivity scales as $T^{1/2}$, where $T$ is the observation time.

In Table 1 I list the *EINSTEIN* XBLs along with their measured 2 keV fluxes, their predicted integral fluxes (above 300 GeV), and the exposure time required to observe this predicted flux with $5\sigma$ significance. Table 2 lists the sources restricted to Milagro's field of view, and Table 3 further restricts the list to low redshift ($z < 0.1$) XBLs. Existing TeV upper limits (from Whipple) are presented in the final column of each table if available.

Of the 8 low redshift XBLs, 3 are predicted to have a flux level sufficient to allow detection in approximately 1 year. It is probably not too surprising that 2 of these sources are Mkn421 and Mkn501; the third source, 1ES1959+650, has not been detected by any experiment and thus has a current upper limit on its quiescent flux of $< 1.3 \times 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}}$ from the Whipple Collaboration. Based on the naive assumptions that I have outlined here, all other sources on this list will require *multi-year* integration times to be observable in their quiescent states.

# 5 Discussion

The technique used here to estimate XBL source counts in Milagro is, admittedly, only slightly better than back-of-the-envelope. I have, however, tried to be optimistic throughout the calculations by assuming that Milagro sensitivity will improve (via improved angular resolution and/or $\gamma$/hadron-separation) by at least a factor of 3, that our threshold will be as low as 300 GeV, and by normalizing to the most optimistic quiescent flux from Mkn421. It should be noted that I have not incorporated source declination effects (ie. reduced source sensitivity), nor have I assumed any absorption on the infrared background.

It is, of course, possible that the assumption of roughly equal power at X-ray and TeV energies is wrong. Perhaps there are XBLs with more power at the higher energies - this would be great news, but difficult to argue for especially in the context of the SSC production model. Assuming a strict correlation between the X-ray and TeV emission is also somewhat controversial; continued multiwavelength campaigns of detected TeV sources will certainly aid in refining these estimates. Whether this correlation holds for both/either quiescent and/or flaring states is a very interesting question and probably depends critically on the source of the low energy photons.

For this memo I have only used the *EINSTEIN* sample of BL Lacs; other catalogs, (ie. ROSAT, ASCA), should also be included to be complete. I have also not included any source variability in estimating the source counts. In my mind strong AGN flares are a *bonus* and we shouldnt assume that nature will cooperate. As I hinted to above, there may also be different physics at work in the flaring and quiescent states; thus, it would be good for our science if both states could be detected.

# 6 Conclusion

I have shown that there are 2 X-ray selected BL Lacs (XBLs) from the *EINSTEIN* Slew Survey potentially observable by Milagro with an exposure of $\sim$1 year: Mkn421 and Mkn501. I have further shown that all other low redshift ($z < 0.1$) *EINSTEIN* XBLs may require multi-year exposures to be detectable: two more XBLs may be observable after 5 years, and another 3 after $\sim$10 years. The technique used here to estimate source counts assumes a correlation between the power emitted by these sources at X-ray energies and the power at TeV energies; this correlation may be appropriate, particularly in the context of the Synchrotron Self-Compton production model. Detection of additional XBLs, ultimately aiding studies of $\gamma$-ray production mechanisms in BL Lacs and analysis of the cosmic infrared background, will require significant improvements to Milagro's sensitivity.

# References


[1] E.S. Perlman et al., Astrophys. Suppl. Ser., 104 (1996) 251.

[2] P. Sreekumar et al., ApJ 464 (1996) 628.

[3] J.H. Buckley et al., Proceedings of the Fourth Compton Symposium, AIP Conf. Proc. 410 (New York:AIP) 1381.

[4] M. Catanese et al., ApJ Lett. 487 (1997) L143.

[5] M.S. Schubnell, et al., astro-ph/9602068.

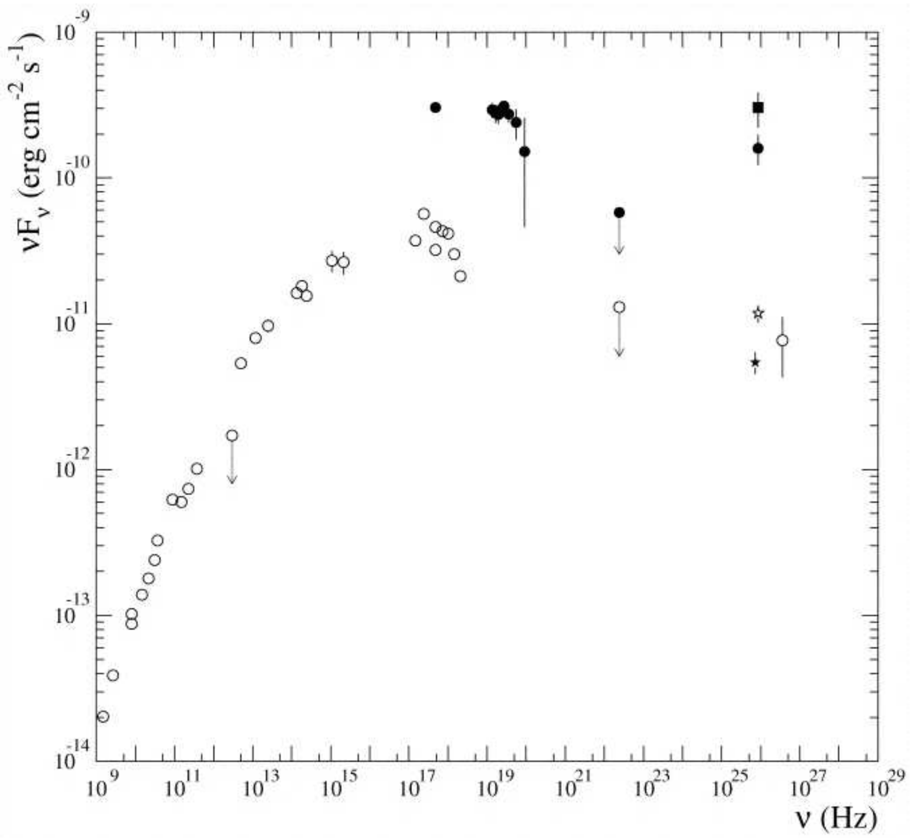


Figure 1: The spectral energy distribution of Mrk 501. The contemporaneous observations taken April 9-15 (filled circles), archival data (open circles), the mean VHE-ray flux in 1995 (filled star), the mean flux in 1996 (open star), and the maximum VHE -ray flux detected on April 16 (square) are indicated. From [4]

| Source | $z$ | $F_\nu$ @ 2 keV ($\mu$Jy) | $I(\geq 300\,\mathrm{GeV})$ ($10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) | $\tau_{reqd}$ (years) | Comments |
|---|---|---|---|---|---|
| 1ES0120+340 | 0.272 | 1.857 | 4.61 | 4.7 | |
| 1ES0145+138 | 0.125 | 2.023 | 5.02 | 3.9 | |
| 1ES0158+003 | 0.299 | 0.667 | 1.65 | 36.7 | |
| 1ES0229+200 | 0.139 | 1.130 | 2.80 | 12.8 | |
| 1ES0323+022 | 0.147 | 1.760 | 4.36 | 5.3 | |
| 1ES0347-121 | 0.188 | 2.319 | 5.75 | 3.0 | |
| 1ES0414-009 | 0.287 | 3.643 | 9.03 | 1.2 | |
| 1ES0446+449 | 0.203 | 0.630 | 1.56 | 41.1 | |
| 1ES0525+713 | 0.249 | 0.798 | 1.98 | 25.5 | |
| 1ES0548-322 | 0.069 | 2.932 | 7.27 | 1.9 | |
| 1ES0737+746 | 0.315 | 0.464 | 1.15 | 75.6 | |
| 1ES0927+500 | 0.188 | 0.674 | 1.67 | 35.9 | |
| 1ES0950+495 | >0.5 | 0.207 | 0.513 | 380 | |
| 1ES1028+511 | 0.239 | 1.883 | 4.67 | 4.6 | |
| 1ES1101+384 | 0.031 | 3.917 | 9.71 | 1.1 | Mkn421 |
| 1ES1118+424 | 0.124 | 1.409 | 3.49 | 8.2 | |
| 1ES1133+704 | 0.046 | 1.789 | 4.44 | 5.1 | Mkn180 |
| 1ES1212+078 | 0.136 | 0.269 | 0.667 | 225 | |
| 1ES1248-296 | 0.487 | 0.794 | 1.97 | 25.8 | |
| 1ES1255+244 | 0.141 | 3.661 | 9.08 | 1.2 | |
| 1ES1312-423 | 0.105 | 0.734 | 1.82 | 3.0 | |
| 1ES1332-295 | 0.513 | 0.268 | 0.665 | 226 | |
| 1ES1402+042 | 0.344 | 0.101 | 0.250 | 1600 | |
| 1ES1440+122 | 0.162 | 0.577 | 1.43 | 48.9 | |
| 1ES1553+113 | 0.360 | 2.566 | 6.36 | 2.5 | |
| 1ES1652+398 | 0.034 | 3.702 | 9.18 | 1.2 | Mkn501 |
| 1ES1727+502 | 0.055 | 1.072 | 2.66 | 14.1 | I Zw 187 |
| 1ES1741+196 | 0.083 | 1.130 | 2.80 | 12.8 | |
| 1ES1853+671 | 0.212 | 0.281 | 0.697 | 206 | |
| 1ES1959+650 | 0.048 | 2.645 | 9.04 | 1.2 | |
| 1ES2005-489 | 0.071 | 2.128 | 5.28 | 3.6 | |
| 1ES2155-304 | 0.117 | 5.746 | 14.25 | 0.5 | |
| 1ES2321+419 | 0.059 | 0.271 | 0.672 | 221.4 | |
| 1ES2326+174 | 0.213 | 0.558 | 1.38 | 52.2 | |
| 1ES2343-151 | 0.226 | 0.298 | 0.739 | 183 | |
| 1ES2344+514 | 0.044 | 1.142 | 2.83 | 12.5 | |

Table 1: *EINSTEIN* XBL Source List, all $z$, $\sim 4\pi$

| Source | $z$ | $F_\nu$ @ 2 keV ($\mu$Jy) | $I(\geq 300\,\mathrm{GeV})$ ($10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) | $\tau_{reqd}$ (years) | Comments |
|---|---|---|---|---|---|
| 1ES0120+340 | 0.272 | 1.857 | 4.61 | 4.7 | |
| 1ES0145+138 | 0.125 | 2.023 | 5.02 | 3.9 | |
| 1ES0229+200 | 0.139 | 1.130 | 2.80 | 12.8 | |
| 1ES0323+022 | 0.147 | 1.760 | 4.36 | 5.3 | |
| 1ES0446+449 | 0.203 | 0.630 | 1.56 | 41.1 | |
| 1ES0525+713 | 0.249 | 0.798 | 1.98 | 25.5 | |
| 1ES0927+500 | 0.188 | 0.674 | 1.67 | 35.9 | |
| 1ES0950+495 | >0.5 | 0.207 | 0.513 | 380 | |
| 1ES1028+511 | 0.239 | 1.883 | 4.67 | 4.6 | |
| 1ES1101+384 | 0.031 | 3.917 | 9.71 | 1.1 | Mkn421 |
| 1ES1118+424 | 0.124 | 1.409 | 3.49 | 8.2 | |
| 1ES1133+704 | 0.046 | 1.789 | 4.44 | 5.1 | Mkn180 |
| 1ES1212+078 | 0.136 | 0.269 | 0.667 | 225 | |
| 1ES1255+244 | 0.141 | 3.661 | 9.08 | 1.2 | |
| 1ES1402+042 | 0.344 | 0.101 | 0.250 | 1600 | |
| 1ES1440+122 | 0.162 | 0.577 | 1.43 | 48.9 | |
| 1ES1553+113 | 0.360 | 2.566 | 6.36 | 2.5 | |
| 1ES1652+398 | 0.034 | 3.702 | 9.18 | 1.2 | Mkn501 |
| 1ES1727+502 | 0.055 | 1.072 | 2.66 | 14.1 | I Zw 187 |
| 1ES1741+196 | 0.083 | 1.130 | 2.80 | 12.8 | |
| 1ES1853+671 | 0.212 | 0.281 | 0.697 | 206 | |
| 1ES1959+650 | 0.048 | 2.645 | 9.04 | 1.2 | |
| 1ES2321+419 | 0.059 | 0.271 | 0.672 | 221.4 | |
| 1ES2326+174 | 0.213 | 0.558 | 1.38 | 52.2 | |
| 1ES2344+514 | 0.044 | 1.142 | 2.83 | 12.5 | |

Table 2: *EINSTEIN* XBL Source List, all $z$, $1^{\mathrm{o}} \leq \mathrm{DEC} \leq 71^{\mathrm{o}}$ ($\pm 35^{\mathrm{o}}$ Milagro Latitude, $35.878^{\mathrm{o}}$)

| Source | $z$ | $F_\nu$ @ 2 keV ($\mu$Jy) | $I(\geq 300\,\mathrm{GeV})$ ($10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) | $\tau_{reqd}$ (years) | Comments |
|---|---|---|---|---|---|
| 1ES1101+384 | 0.031 | 3.917 | 9.71 | 1.1 | Mkn421 |
| 1ES1133+704 | 0.046 | 1.789 | 4.44 | 5.1 | Mkn180, $< 1.1 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| 1ES1652+398 | 0.034 | 3.702 | 9.18 | 1.2 | Mkn501 |
| 1ES1727+502 | 0.055 | 1.072 | 2.66 | 14.1 | I Zw 187, $< 0.69 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| 1ES1741+196 | 0.083 | 1.130 | 2.80 | 12.8 | $< 0.48 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| 1ES1959+650 | 0.048 | 2.645 | 9.04 | 1.2 | $< 1.3 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| 1ES2321+419 | 0.059 | 0.271 | 0.672 | 221.4 | $< 1.1 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| 1ES2344+514 | 0.044 | 1.142 | 2.83 | 12.5 | |
| | | | | 5.1 | $1.1 \pm 0.4 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (1995/1996) |
| | | | | - | $< 8.2 \times 10^{-12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (1996/1997) |
| | | | | 1.4 | $6.6 \pm 1.9 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (1995 flare) |

Table 3: *EINSTEIN* XBL Source List, $z \leq 0.1$, $1^{\circ} \leq \mathrm{DEC} \leq 71^{\circ}$ ($\pm 35^{\circ}$ Milagro Latitude, $35.878^{\circ}$)