Studies of Nearby Blazars with Milagro

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Abstract. We have examined a sample of 47 blazars for evidence of TeV emission in the data collected with Milagro since 2000. Emission is clearly seen from Markarian 421, with the detected flux concentrated in two intervals coinciding with strong X-ray emission. No significant flux is detected from any of the other AGN, and flux limits are presented. For the blazars I Zw 187 and RGB 1725+118 the limits – including the effects of absorption by extragalactic background light (EBL) – exclude the empirical model of Fossati *et al.* for the flux.

MILAGRO

The Milagro detector is a water-filled reservoir instrumented with 723 photomultiplier tubes (PMTs) to monitor the northern sky for astrophysical gamma-ray emission near 1 TeV. It is located at 35.88° N, 106.68° W and is 2630 m above sea level. The opaque cover over the reservoir allows continuous operation. The high duty cycle (>90%) and wide aperture (∼2 sr) allow for the detection of TeV flaring behavior associated with AGN, even during daytime transits. The incident direction of gamma-ray showers recorded by Milagro is reconstructed with a resolution of 0.75° using the time of arrival information from the PMTs. The majority (∼90%) of background cosmic ray showers are rejected using the light amplitudes recorded in the PMTs at the bottom of the reservoir, as described in R. Atkins *et al.* [1], while retaining about 50% of the gamma-ray showers.

Other papers in these proceedings describe results from Milagro on new unidentified sources [2], gamma-ray bursts [3], galactic plane emission [4], and a search for WIMP annihilation [5].

THE BLAZAR SAMPLE AND DATA SET

We selected a sample of 47 nearby blazars within the Milagro field of view to study for steady emission and flaring emission on time scales as short as 8 days. We use Milagro

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[1] R. Atkins, W. Benbow, D. Berley, E. Blaufuss, D. G. Coyne, T. DeYoung, B. L. Dingus, D. E. Dorfan, R. W. Ellsworth, L. Fleysher, R. Fleysher, M. M. Gonzalez, J. A. Goodman, E. Hays, C. M. Hoffman, L. A. Kelley, C. P. Lansdell, J. T. Linnemann, J. E. McEnery, A. I. Mincer, M. F. Morales, P. Nemethy, D. Noyes, J. M. Ryan, F. W. Samuelson, P. M. Saz Parkinson, A. Shoup, G. Sinnis, A. J. Smith, G. W. Sullivan, D. A. Williams, M. E. Wilson, X. W. Xu and G. B. Yodh.

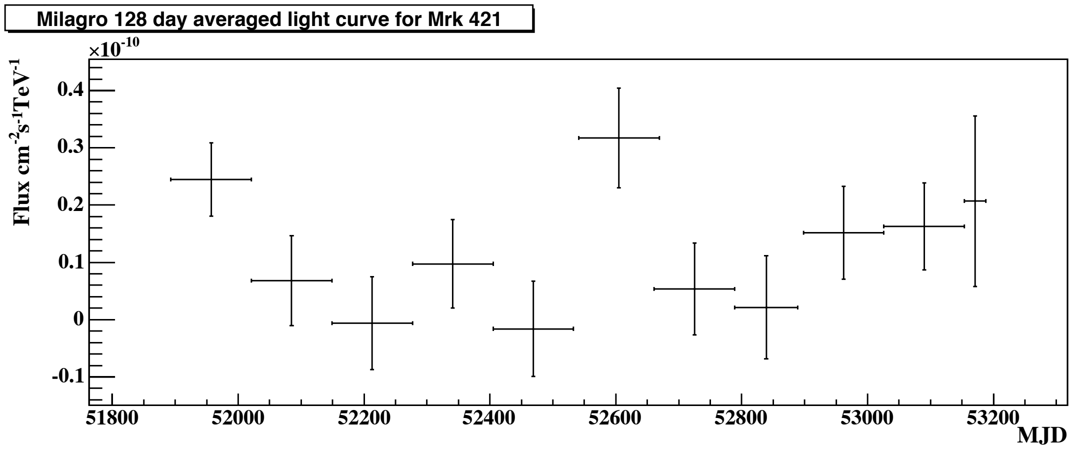

FIGURE 1. The Milagro light curve for Markarian 421, with the flux averaged in 128-day bins. The 1-σ errors on the flux for each bin are shown.

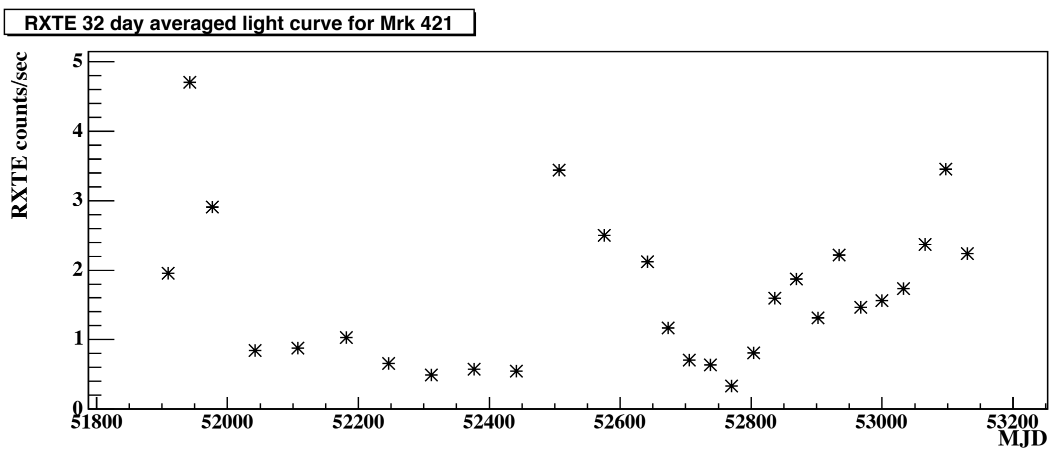

FIGURE 2. Markarian 421 light curve from RXTE All-Sky Monitor data. The flux has been averaged in 32-day bins.

data collected from 15 December 2000 to 8 September 2003. Details of the analysis method are described in Hays [6].

The majority of the sample (27 blazars) are TeV candidate BL Lac objects studied by Costamante and Ghisellini [7]. Selecting z<0.1 objects from the list of Perlman [8] yields 14 HBLs and 5 FSRQs and from the AGN detected by EGRET [9] adds 2 LBLs. The sample also includes 5 blazars which have been previously detected at TeV energies: Mrk 421 [10], Mrk 501 [11], 1ES2344+514 [12], 1ES1426+428 [13], and 1ES1959+650 [14]. Some blazars in the sample are selected by more than one of these criteria.

The only blazar from this compilation detected as a source in these data is Markarian 421. It is discussed further below. Limits for the flux from the other 46 AGN are given in Tables 1 and 2.

TABLE 1. Milagro 95% confidence level upper limits for the blazar sample for emission time intervals from 8 days to the full data set of 906 days. The limits given are the differential flux, not including the effect of absorption by collisions with extragalactic background light, expressed as the factor multiplying 10^{-11} $(E/TeV)^{-2.5}$ cm^{-2} s^{-1} TeV^{-1}. The results are continued in Table 2.

		RA	Dec		Upper Limits by Time Interval (days)						
Name	**Type**	**(J2000)**	**(J2000)**	**Redshift**	**8**	**16**	**32**	**64**	**128**	**256**	**906**
III Zw 002	FSRQ	00 10 30.8	+10 58 13	0.09	25.4	19.6	12	4.8	3.4	1.8	0.65
1ES 0033+595	HBL	00 35 52.6	+59 50 05	0.086	22.2	15.4	11.8	7.9	5.5	3.1	0.83
RGB 0110+418	HBL	01 10 04.8	+41 49 51	0.096	16.5	8.5	5.4	3.6	2.5	1.5	0.3
1ES 0120+340	HBL	01 23 08.5	+34 20 48	0.272	14	10.1	6.1	4.3	2.6	1.9	0.7
RGB 0136+391	HBL	01 36 32.4	+39 05 59	Unknown	14	9	6.9	3.7	2.8	1.9	0.35
B2 0138+39B	FSRQ	01 41 57.9	+39 23 30	0.08	13.2	8.4	5.4	4.1	2.6	1.8	0.32
RGB 0152+017	HBL	01 52 39.6	+01 47 17	0.08	47.7	31.1	22.8	18.1	10.8	7	2.12
RGB 0153+712	HBL	01 53 25.9	+71 15 06	0.022	48.8	31.1	19.5	10.8	8.5	5.4	1.91
RGB 0214+517	HBL	02 14 17.9	+51 44 52	0.049	17.2	12.8	6.4	4.2	3.2	2.3	0.64
3C 66A	LBL	02 22 39.6	+43 02 08	0.444*	14.5	12.1	7.4	4.5	3	2.1	0.7
1ES 0229+200	HBL	02 32 48.4	+20 17 16	0.139	16.6	11	6.8	4.8	3.4	2.5	1.1
RGB 0314+247	HBL	03 14 02.5	+24 44 33	0.054	14.7	11.3	7.5	3.9	3	1.6	0.49
B2 0321+33	FSRQ	03 24 41.2	+34 10 46	0.062	13.6	8.4	5.2	3.5	2.3	1.7	0.62
1H 0323+022	HBL	03 26 14.0	+02 25 15	0.147	47.1	38.5	26.8	18.7	8.5	5.2	1.88
1H 0414+009	HBL	04 16 52.5	+01 05 24	0.287	59.7	33.5	28.3	17.4	11.8	6.1	1.94
1ES 0647+250	HBL	06 50 46.5	+25 03 00	Unknown	15.1	9.3	6.3	3.6	2.5	1.7	0.38
RGB 0656+426	HBL	06 56 10.7	+42 37 03	0.059	13.2	7.9	5.3	4.4	1.4	1	0.41
1ES 0806+524	HBL	08 09 49.1	+52 18 59	0.138	16.5	11.7	8.5	5.5	4.4	2	0.58
RGB 0812+026	HBL	08 12 01.9	+02 37 33	Unknown	45.5	29.9	23.2	14.7	10.9	5.4	1.3
OJ 287	HBL	08 54 48.9	+20 06 31	0.306	14.6	11.7	7.2	5.7	3.1	2.3	0.72
1H 1013+498	HBL	10 15 04.1	+49 26 01	0.2	17.4	10.6	7	4.4	3.2	2.2	0.52
1ES 1028+511	HBL	10 31 18.4	+50 53 36	0.361	16.4	11.4	7.5	4.8	2.4	1.4	0.34
RGB 1117+202	HBL	11 17 06.2	+20 14 07	0.139	15.9	10.1	8.8	5.6	3	1.8	0.69

* tentative redshift

MARKARIAN 421

An extended data set, from 15 Dec 2000 through 2 July 2004, has been analyzed for Markarian 421. Because of the source variability [15], the significance and average flux vary depending on the dates spanned by the data set. In this sample, comprising a total exposure of about 1180 days, Markarian 421 is detected with a significance of 4.7 σ, with a corresponding preliminary flux

$$dN/dE = (1.09 \pm 0.24) \times 10^{-11} (E/TeV)^{-2.5} cm^{-2} s^{-1} TeV^{-1} .$$

TABLE 2. Continuation of Table 1.

Name	Type	RA (J2000)	Dec (J2000)	Redshift	Upper Limits by Time Interval (days) 8	16	32	64	128	256	906
MRK 180	HBL	11 36 26.4	+70 09 27	0.045	56.4	25.5	18.3	11.2	7.9	4.1	1.11
RGB 1136+676	HBL	11 36 30.1	+67 37 04	0.135	38.7	24.5	19.2	10.2	7.2	4.1	1.5
ON 325	HBL	12 17 52.1	+30 07 01	0.237	12.9	9.4	6.7	4.2	2.7	2.2	0.77
1H 1219+301	HBL	12 21 21.9	+30 10 37	0.182	16.1	10.8	7.7	4.9	3.4	2.5	1
W Comae	LBL	12 21 31.7	+28 13 58	0.102	14.3	8.5	6.9	4.7	2.9	1.9	0.63
RGB 1413+436	FSRQ	14 13 43.8	+43 39 45	0.09	16.8	13.9	8.4	4.8	3.8	2.2	1.03
RGB 1417+257	HBL	14 17 56.7	+25 43 26	0.237	18.2	10.3	6.4	4.2	3.2	2.1	1.11
H 1426+428	HBL	14 28 32.7	+42 40 21	0.129	12.7	7.6	5.7	4	2.7	1.3	0.35
1ES 1440+122	HBL	14 42 48.2	+12 00 40	0.162	21.7	15	8.7	5.3	3.5	2.6	0.73
RGB 1532+302	HBL	15 32 02.2	+30 16 29	0.064	16.6	11.4	6.6	4.5	3.4	1.8	0.66
1ES 1553+302	HBL	15 55 43.0	+11 11 24	0.36	24.9	13	10	7	5	1.9	0.7
RGB 1610+671	HBL	16 10 02.4	+67 10 12	0.067	33.3	28.3	18.3	10.4	5.5	3.6	2.04
MRK 501	HBL	16 53 52.2	+39 45 37	0.034	16.4	8.9	5.6	3	2.1	1.2	0.56
RGB 1725+118	HBL	17 25 04.3	+11 52 15	0.018*	25.5	14	11	7.6	5.5	3.5	1.58
I Zw 187	HBL	17 27 18.6	+50 13 10	0.055	19	8.4	5.3	3.2	1.9	1.2	0.29
1ES 1741+196	HBL	17 43 57.8	+19 35 09	0.084	21.2	11	8.2	6	3	2.2	1.11
3C 371	LBL	18 06 50.6	+69 49 12	0.051	42.3	28.1	21.5	12.8	8.1	5.7	1.05
1ES 1959+650	HBL	19 59 59.9	+65 08 55	0.047	32.3	21.8	17.6	7.7	4	2.5	0.57
BL Lacertae	LBL	22 02 43.3	+42 16 40	0.069	12.9	9.8	5.8	5.1	2.7	1.8	0.59
II Zw 171	FSRQ	22 11 53.7	+18 41 51	0.07	20.8	14.7	7.6	6.9	3	1.5	0.5
RGB 2322+346	HBL	23 22 44.0	+34 36 14	0.098	15.4	10.9	5.8	4.3	3.2	2.1	0.69
1ES 2321+419	HBL	23 23 52.1	+42 10 59	0.059	15.4	10	5.6	3.3	1.9	1.1	0.36
1ES 2344+514	HBL	23 47 04.8	+51 42 18	0.044	20.4	14.1	8.1	6.4	4.1	3.1	0.81

* tentative redshift

Averaged light curves for both the Milagro data and data from the RXTE All-Sky Monitor are shown in Figures 1 and 2. The apparent correlation is under further study.

I ZW 187 AND RGB 1725+118

The Milagro upper limits for two sources – I Zw 187 and RGB 1725+118 – are sufficiently tight to constrain published emission models, even after taking absorption by extragalactic background light into account. The Milagro upper limits are superimposed

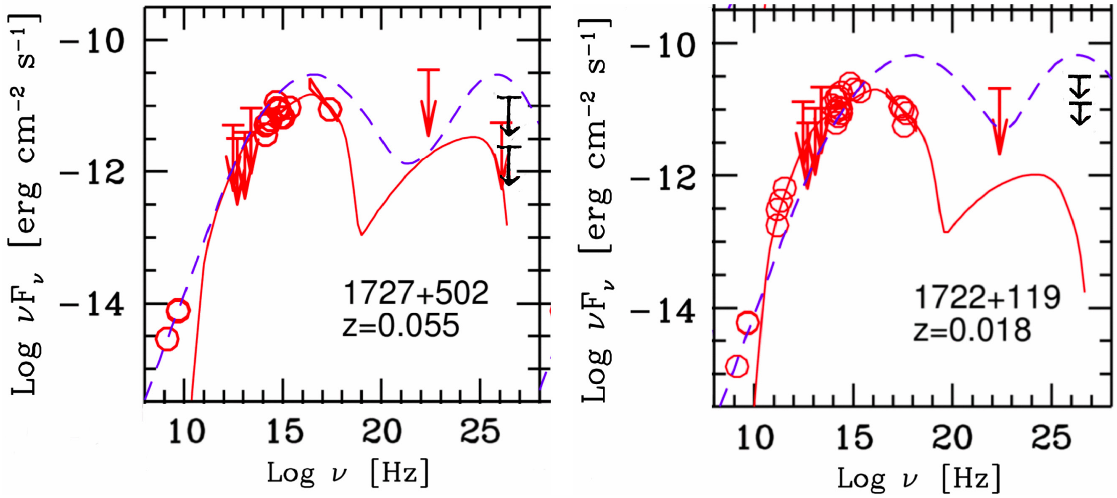

FIGURE 3. Models for the spectral energy distribution of I Zw 187 (left) and RGB 1725+118 (right), from the work of Costamante and Ghisellini [7]. The solid curve is an SSC model, and the dashed curve is the modified Fossati *et al.* model. The Milagro upper limits on the flux are at the right in each graph, at $\mathrm{Log}\nu \sim 26.3$. In each case, the higher of the two limits includes the effect of absorption by extragalactic background light, and the lower one does not.

in Figure 3 on the corresponding figures from Costamante and Ghisellini [7]. In each case, the higher of the two limits assumes the spectrum from the modified Fossati et al. model (dashes) and includes absorption by the EBL[2] as predicted by [16]. Using the EBL models of J. R. Primack *et al.* [17] gives similar results. The lower, more constraining, limit in each graph is without the effect of EBL absorption. Even after accounting for absorption, the limits are in conflict with the model; the SSC model (the solid curve) is still allowed.

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[2] The redshift, and hence the EBL correction, for RGB 1725+118 is uncertain because the redshift measurement was made using only one absorption line.

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