02/14/01

Measured Fluxes of the Crab and Mrk 421, and Expectations for Milagro

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The data analyzers are busily working over the Milagro data to see if we detect signals from the Crab and Mrk 421 (which is presently flaring). The purpose of this note is to record the measured fluxes for these two objects and understand the resulting implications for Milagro. In my earlier memos ("Flux Measurements by Air Cerenkov Telescopes", Milagro memo #37, and "Measured Fluxes from the Crab and Markarian 501 and Expectations for Milagrito" - Milagro memo #47), I discussed how source fluxes are measured by air Cerenkov telescopes. I will concentrate here on Whipple and the HEGRA array, as these detectors have the best measurements.

The Crab

The Crab is supposedly a steady gamma-ray source, so the flux measured one year can be compared with a measurements made in different years. The Crab flux has been measured by both Whipple (Hillas *et al*., Ap J. **503**, 744 [1998]) and the HEGRA array (Aharonian *et al*., Ap. J. **539**, 317 [2000]). The spectrum is fit by each group to a simple power law. The fits to the differential spectra are:

$\Phi = (3.20 \pm 0.17 \pm 0.6) \times 10^{-7} (E/1\ \mathrm{TeV})^{-(2.49 \pm 0.06 \pm 0.04)}\ \mathrm{m^{-2}\, s^{-1}\, TeV^{-1}}$ [Whipple]; and

$\Phi = (2.79 \pm 0.02 \pm 0.5) \times 10^{-7} (E/1\ \mathrm{TeV})^{-(2.59 \pm 0.03 \pm 0.05)}\ \mathrm{m^{-2}\, s^{-1}\, TeV^{-1}}$ [HEGRA].

The first errors are statistical and the second errors are systematic. Strictly speaking, the Whipple spectrum is for 500 GeV $\leq E_\gamma \leq$ 8 TeV, and the HEGRA spectrum is for 500 GeV $\leq E_\gamma \leq$ 20 TeV, although the systematic errors grow markedly below 1 TeV for HEGRA. The HEGRA result has better statistics but the quoted systematic errors, which dominate, are comparable. Personally, I believe that the HEGRA array has a better handle on measuring the shower core position so that at least some of their systematic errors should be smaller.

Figure 1 below, from the HEGRA paper, shows recent measurements of the differential spectrum of the Crab. The measurements agree with one another except for those from Tibet, which appear to be a factor of ~3 higher than the others.

A newer measurement of the Crab spectrum was published by Whipple as part of checking the technique of extracting spectra from large-zenith-angle ($55° \leq \theta \leq 60°$) data (Krennrich *et al*., Ap. J. **511**, 149 [1999]):

$$\Phi = 3.20 \times 10^{-7} (E/1\ \mathrm{TeV})^{-(2.59 \pm 0.15 \pm 0.15)}\ \mathrm{m^{-2}\, s^{-1}\, TeV^{-1}}.$$

This result has poorer statistics, but is consistent with the other measurements. The conclusion of the Crab results is a consistent picture, except for the Tibet result.

Markarian 421

Unlike the Crab, Markarian 421 is not a steady source. When Markarian 421 is not flaring, the flux is too low to allow the spectrum to be measured. The measurements of the differential spectrum are made during flares when the flux is varying markedly. Thus it makes sense to compare different measurements of the spectral shape but not of the source strength. Recall that the spectrum of Markarian 501 is not fit well by a simple power law: the Mrk501 spectrum is markedly curved. We might expect this to be the case for Markarian 421 also.

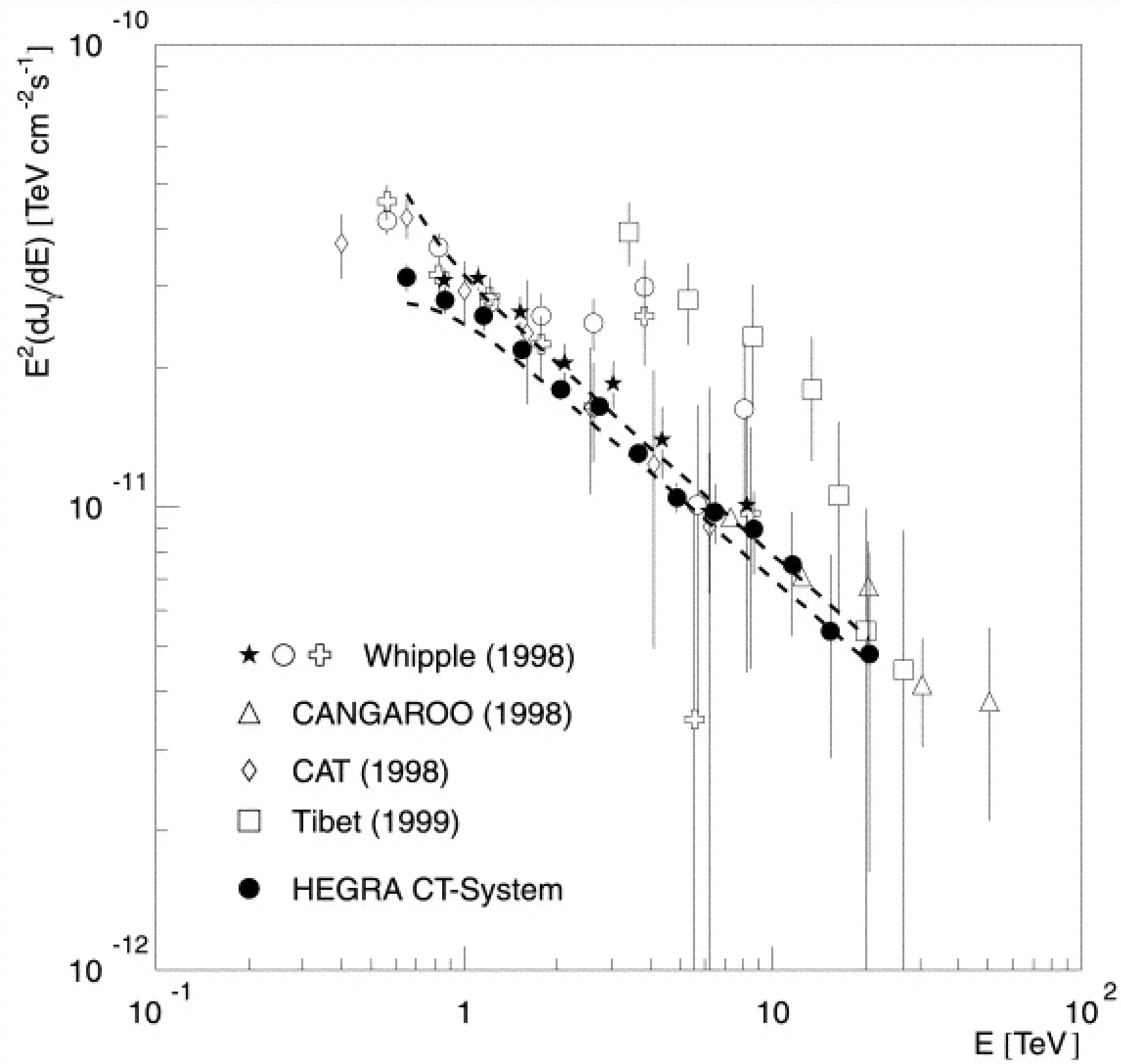

Figure 1: The differential spectrum from the Crab as measured by the HEGRA array, Whipple, CANGAROO, CAT, and Tibet. The dashed curves show the limits of the systematic error for the HEGRA data. From Aharonian *et al*., Ap. J. **539**, 317 [2000].

Whipple published a spectrum for Markarian 421 in Krennrich *et al*. (see above). The data is primarily from a huge flare on May 7, 1996 (~3 hours on-source with an average of 7.4 "Crab units"). Additional data are from a smaller flare on May 15, 1996 (27 minutes on-source at 2.8 Crab units), and large-zenith-angle data from a flare on June 20, 29, 30, 1995 (5 hours on-source at 3.3 Crab units). Figure 2 shows these measurements.

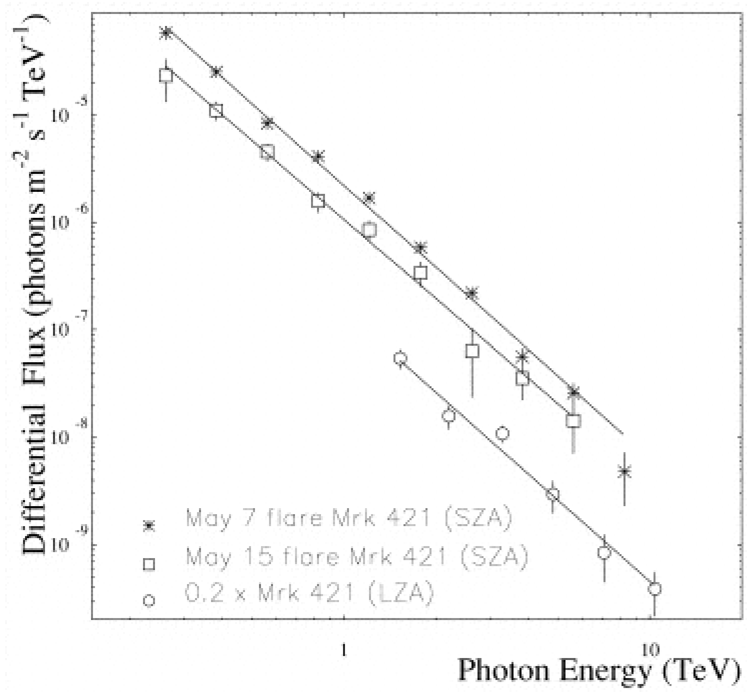

Figure 2: Energy spectra of Markarian 421 from the Whipple data for three separate flares. From Krennrich *et al*., Ap. J. **511**, 149 [1999].

Because the spectral shapes appear to be similar, they combine them (allowing the normalizations to vary) and obtain: $\Phi \propto E^{-2.54 \pm 0.03 \pm 0.10}$, for 260 GeV $\leq E_\gamma \leq$ 10 TeV with $\chi^2 = 31.5$ for 21 dof. A curved fit,

$$\Phi = (2.4 \pm 0.1 \pm 0.3) \times 10^{-6} (E/1\ \text{TeV})^{-[2.47 \pm 0.04 \pm 0.05 - (0.28 \pm 0.09) \log_{10}(E)]}\ \text{m}^{-2}\,\text{s}^{-1}\,\text{TeV}^{-1},$$

gives $\chi^2 = 21.5$ for 20 dof. The curvature is quite small over this range. Looking at the errors in Figure 2, we see that these shapes are dominated by the May 7, 1996 flare. Whipple also gives a spectral index for the 1995-6 observing season excluding the huge May 7, 1996 flare of -2.96 ± 0.22 (Zweerink *et al.* Ap. J. **490**, L141 [1997]), suggesting that the May 7th flare had a harder spectrum.

HEGRA has published the Markarian 421 spectrum from data taken in 1997 and 1998 (Aharonian *et al*., A&A **350**, 757 [1999]). Their fit to a simple power law yields:

$$\Phi = (12.1 \pm 0.5 \pm 4.3) \times 10^{-8} (E/1\ \text{TeV})^{-(3.09 \pm 0.07 \pm 0.10)}\ \text{m}^{-2}\,\text{s}^{-1}\,\text{TeV}^{-1}.$$

This fit has $\chi^2 = 23.5$ for 10 dof . They obtain a slightly better fit ($\chi^2 = 16.8$ for 9 dof) using the shape $(E/1\ \text{TeV})^{-(2.5 \pm 0.4)} \exp(-E/E_o)$ with $E_o = 2.8$ (+2.0, -0.9) TeV. While the HEGRA spectrum is softer than the overall Whipple spectrum (an index of 3.09 vs. 2.54), the errors lead them to conclude that the evidence for spectral hardening during the intense flare of May 7, 1996 is only marginally significant. Figure 3 shows the HEGRA result.

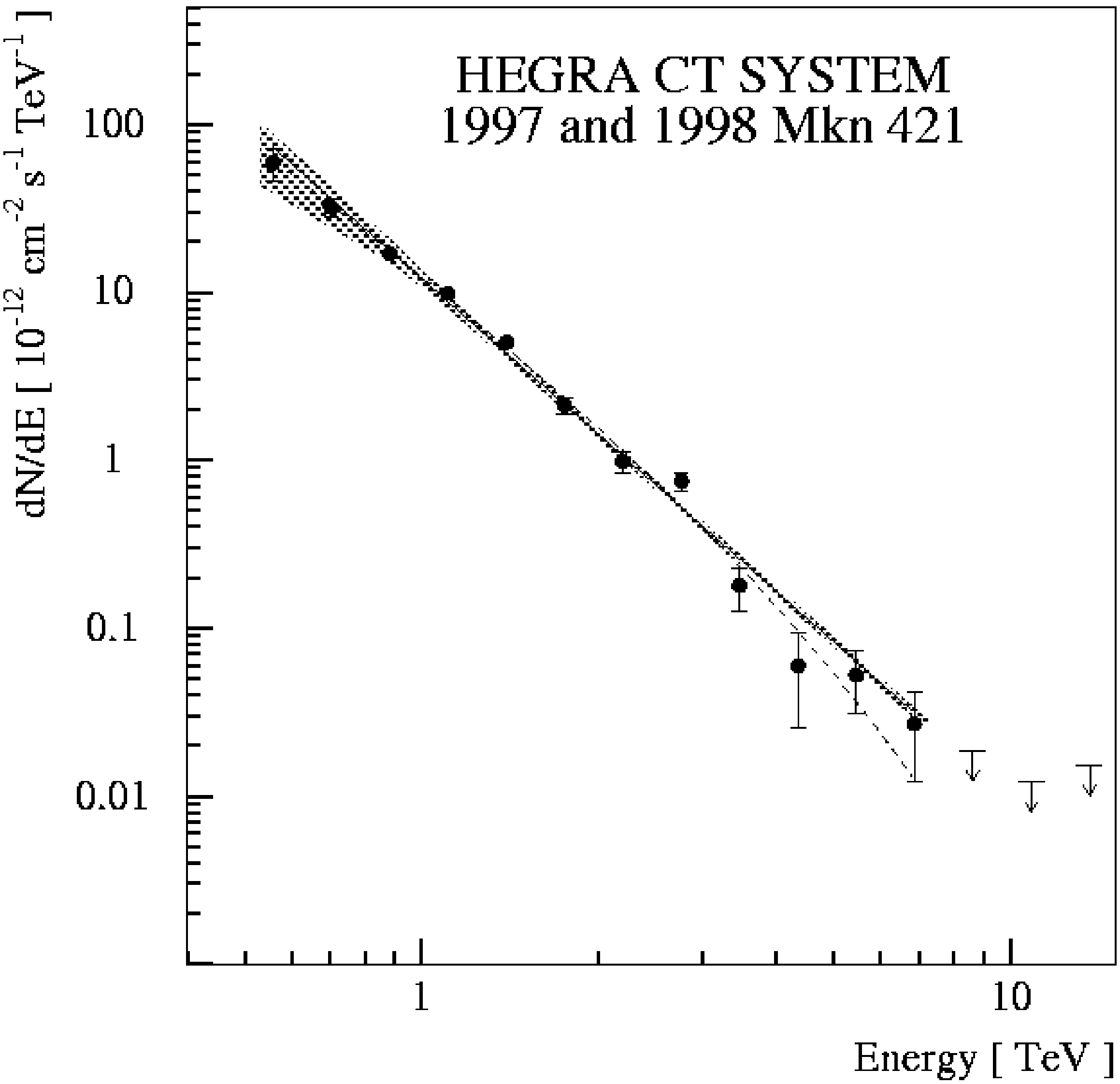

Figure 3: The HEGRA time-averaged energy spectrum from Mrk 421. The hatched area gives the estimated systematic uncertainty in spectral shape. The solid line shows the simple power-law fit, and the dotted curve is the fit with the exponential cutoff. From Aharonian *et al*. A&A **350**, 757 [1999].

Discussion

The Whipple and HEGRA determinations of the flux from the Crab are consistent with each other and with a simple power law $\propto E^{-(2.54\pm 0.1)}$, slightly harder than the cosmic-ray spectrum. Other measurements are consistent with this up to at least 50 TeV except for the Tibet measurement, which appears to give a flux a factor of ~3 high.

The situation with Markarian 421 is not quite as simple, at least partially because of the flaring nature of the source. Both Whipple and HEGRA can adequately fit their spectra with a simple power law, although adding curvature slightly improves the fits. HEGRA's result is $\propto E^{-3.1}$, considerably softer than the Crab. Whipple's result, $E^{-2.5}$, is dominated by a huge flare on May 7, 1996. This might indicate some disagreement with HEGRA or a flare with a different spectral index.

Markarian 421 is flaring at present. Table 1 shows the data from HEGRA's web site (http://www-hegra.desy.de/mrk-421/). The average is 1.9 Crab units, where a HEGRA "Crab unit" is defined to be the integral flux above 0.5 TeV (again from their web site). Of course we do not know what the spectral shape is now. I shall use the shape from HEGRA, which seems to be appropriate for all times except the May 7, 1996 burst.

Date	CT System Flux (Crab Units)
1/16-17	0.8 ±0.2
1/17-18	2.5 ±0.3
1/18-19	1.5 ±0.2
1/19-20	0.9 ±0.1
1/20-21	1.8 ±0.3
1/21-22	2.9 ±0.4
1/22-23	2.6 ±0.3
1/23-24	1.5 ±0.2
1/24-25	1.4 ±0.1
1/25-26	1.9 ±0.2
1/26-27	1.8 ±0.2
1/27-28	1.3 ±0.1
1/28-29	1.4 ±0.1
1/29-30	1.4 ±0.1
1/30-31	4.3 ±0.2
1/31-2/1	2.9 ±0.2
2/1-2	2.5 ±0.2
2/2-3	1.5 ±0.1
2/3-4	1.8 ±0.2
2/4-5	1.5 ±0.2
MOON	-
2/13-14	2.4 ±0.3
Average	**1.9 ±0.8**

Table1: Results from the HEGRA CT array on Markarian 421 for January, and February 2001. From http://www-hegra.desy.de/mrk-421/. The average flux is 1.9 Crab units, with a standard deviation of 0.8.

We want to estimate the relative event rates for the Crab and the present Markarian 421 flare for Milagro. Converting from a ratio of integral fluxes to a ratio of differential fluxes, 2 Crab units implies that $\Phi_{Crab}(1\text{ TeV}) / \Phi_{Mrk421}(1\text{ TeV}) = 1.9$. Thus

$$\Phi_{Mrk421} = (1.9) \times (2.8 \times 10^{-7})\, (E/1\text{ TeV})^{-3.09} = 5.3 \times 10^{-7}\, (E/1\text{ TeV})^{-3.09}\ \text{m}^{-2}\,\text{s}^{-1}\,\text{TeV}^{-1}.$$

Figure 4 shows the Crab and Mrk421 fluxes corresponding to the above assumptions. We want to compare the relative signal sizes in Milagro for Mrk421 at a declination of 38° and a strength of 2 Crab units with the Crab (at declination 22°). According to an e-mail message of 10/2/00 from Julie McEnery, the relative number of events in Milagro for sources at declinations 22° and 38° with $E^{-2.4}$ spectra is $E_{38}/ E_{22} = 1.4$, while the ratio of the number of background events is $B_{38}/ B_{22} = 1.2$. Thus the ratio of significances for an almost Crab-like source at these two declinations is

$$S_{38}/ S_{22} = 1.4 / \sqrt{1.2} = 1.3.$$

From Julie's note, the median energy for an $E^{-2.4}$ spectrum at a declination of 38° (22°) is ~6 (7) TeV; some results I obtained from Andy give a median energy of ~3 TeV for an $E^{-2.5}$ spectrum at 22°, indicating that the median energy depends strongly on the spectral shape. The median energy for Mrk421 would be even lower because of its softer spectrum. Because the Mrk421 flux is ~1.9x the Crab flux at 1 TeV (for 2 HEGRA) Crab units, I guess that 1 Mrk421 day at this level should give a significance of (1.3) x (1.9) = 2.5 times the significance of a Crab day. If we expect to see the Crab at 5σ per year (0.25σ/day), we would expect to see 0.6σ/day from Mrk421 at a level of 2 Crab units. At this rate, it would take 3 weeks to reach 3σ.

One other minor point, throwing source spectra $\propto E^{-2.4}$ is probably not as useful as throwing $\propto E^{-2.6}$, which is closer to the Crab spectrum.

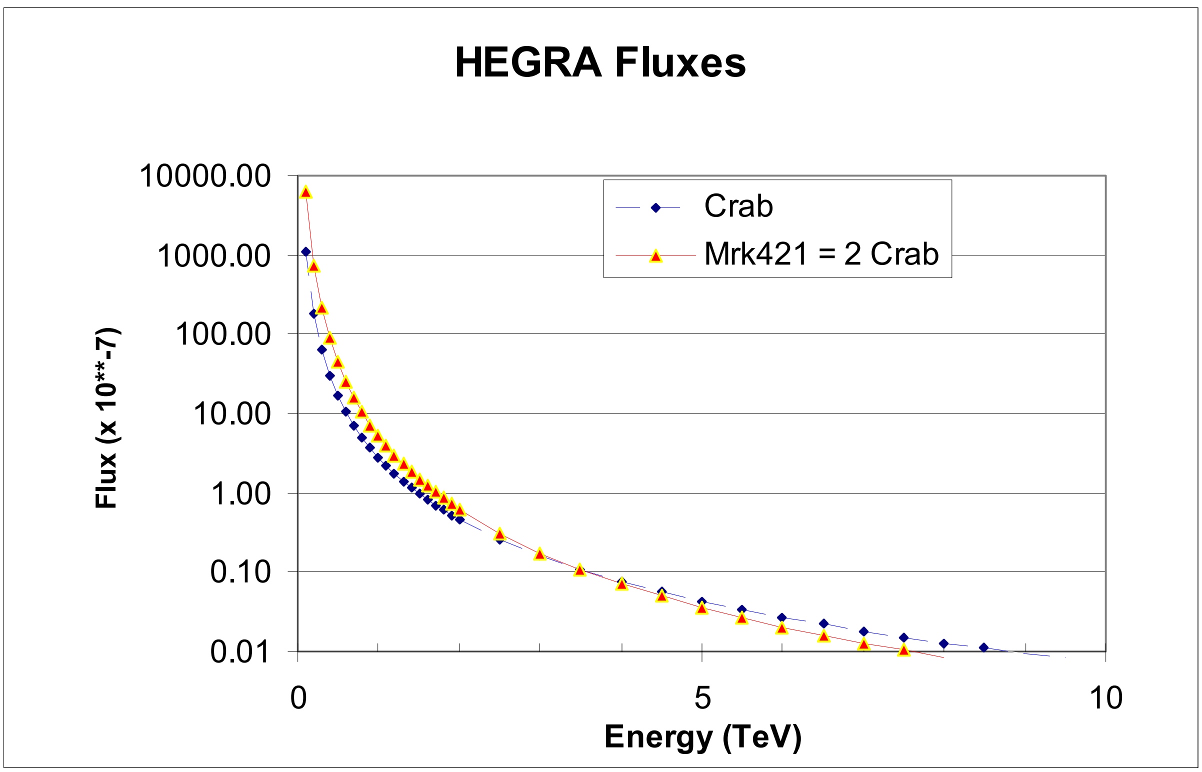

Figure 4: The spectral shapes for Markarian 421 as measured by Whipple and HEGRA. The Markarian 421 flux is normalized to equal 2 "Crab units" (HEGRA definition).