Measured Fluxes from the Crab and Markarian 501 and Expectations for Milagrito

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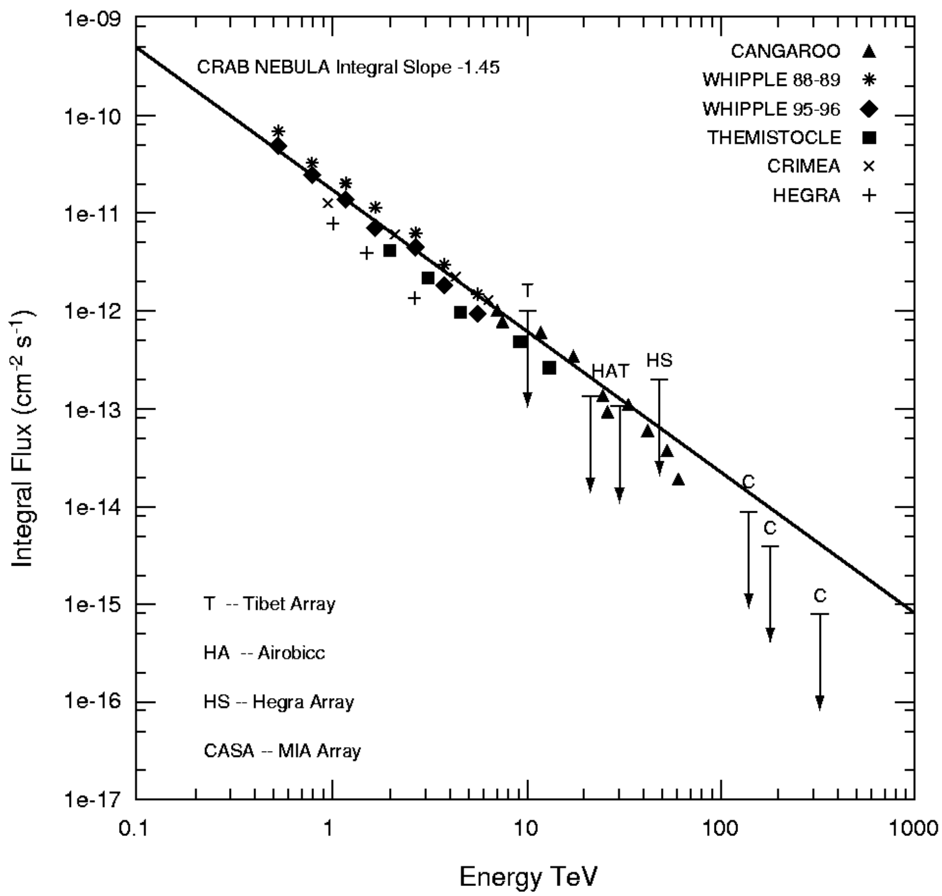
The Crab

The flux from the Crab has been well measured by a number of air Cerenkov telescopes (ACTs). All indications are that the flux is well described by a simple power law and is constant in time. The flux, as measured by Whipple (Hillas *et. al.,* Ap. J. **503**, 744 [1998]) is:

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

A plot of measured Crab fluxes is shown below:



A new measurement from the HEGRA ACT array, not on this plot, (Konopelko *et. al.,* astro-ph/9901094) gives:

$$\Phi = (2.7 \pm 0.2 \pm 0.8) \times 10^{-7} (E/1\mathrm{Tev})^{-(2.61 \pm 0.06 \pm 0.1)}\ m^{-2}\, s^{-1}\, TeV^{-1}.$$

Note that these measurements have systematic uncertainties of 20-30% in the magnitude of the flux. The flux from the Crab is a power law up to at least 20 TeV. The spectrum has also been measured up to 50 TeV using the large zenith-angle technique by CANGAROO (Tanimori *et. al.,* ApJ. **492**, L33 [1998]). There is also good evidence that the flux from the Crab has been steady over at least the past ~10 years.

Markarian 501

In contrast to the Crab, Markarian 501 has shown extremely variable high-energy emission over the past few years. Observations by Whipple (Quinn *et. al.,* Ap. J. **456**, L83 [1996]; Quinn *et. al.,* astro-ph/9903088) showed low-level emission in 1995-6 (at the level of 10-20% of the Crab) but much stronger emission in 1997 with well-documented strong flares. The data from 1998 (see the Quinn preprint) show some strong emission in March, 1998 but relatively low fluxes for the rest of 1998: note that Markarian 501 cannot be observed by ACTs between October and February because it is not up at night. Of course for Milagrito, we are concerned with the flux from Markarian 501 between February, 1997 and April, 1998.

During 1997, Markarian 501 was observed by a number of ACTs (see, *e.g.* Protheroe *et. al.*, astro-ph/9710118). The HEGRA stand-alone imaging ACTs, CT1 and CT2, have the most extensive data set including data with CT1 at reduced high-voltage during periods with the moon. The table below gives the number of days in each month of 1997-8 in which there is at least one observation of Markarian 501 and the average flux for the month (I'll explain the units below). In many cases there are several observations on a single day. However, at present I can only find data from Whipple for 1998.

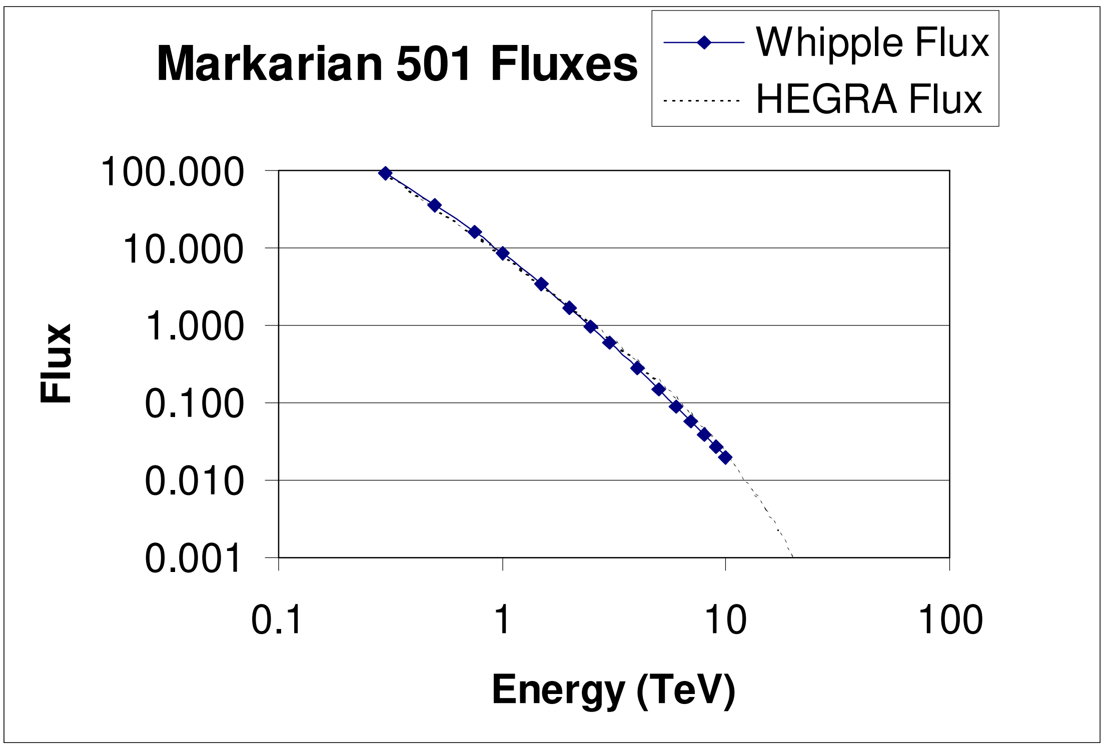
Month	Number of Days with ≥1 Observation of Mrk 501	Approx. Average Flux (Crab units)
2/97	5	0.6
3/97	17	1.0
4/97	23	1.5
5/97	22	1.7
6/97	22	1.7
7/97	22	1.9
8/97	21	1.2
9/97	20	1.1
10/97	12	1.0
11/97-2/98	0	?
Early 3/98	6	1.9
Late 3/98	3	0.0
Late 4/98	9	0.08

Given the highly variable emission from Markarian 501, it is difficult to quote an average flux. However, the strong emission makes it possible to measure the shape of the spectrum. In fact, the average spectrum for 1997 has been published by Whipple (Samuelson *et. al.,* ApJ. **501**, L17 [1998]) and given in a preprint by the HEGRA stereo system of ACTs (Konopelko *et. al.,* astro-ph/9901093). The Whipple data covers their observations from Feb. 10 - Jun. 11, 1997, while the HEGRA data is from March 16 - Oct. 1, 1997. Because the data do not cover the same times, one should not expect them to agree on the magnitude of the flux; surprisingly they do. The fluxes from Whipple and HEGRA for 1997 are:

$$\Phi_W = (8.6 \pm 0.3 \pm 0.7) \times 10^{-7} (E/1\mathrm{Tev})^{-(2.20\pm0.04\pm0.05)-(0.45\pm0.07)\log_{10}E}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1};$$

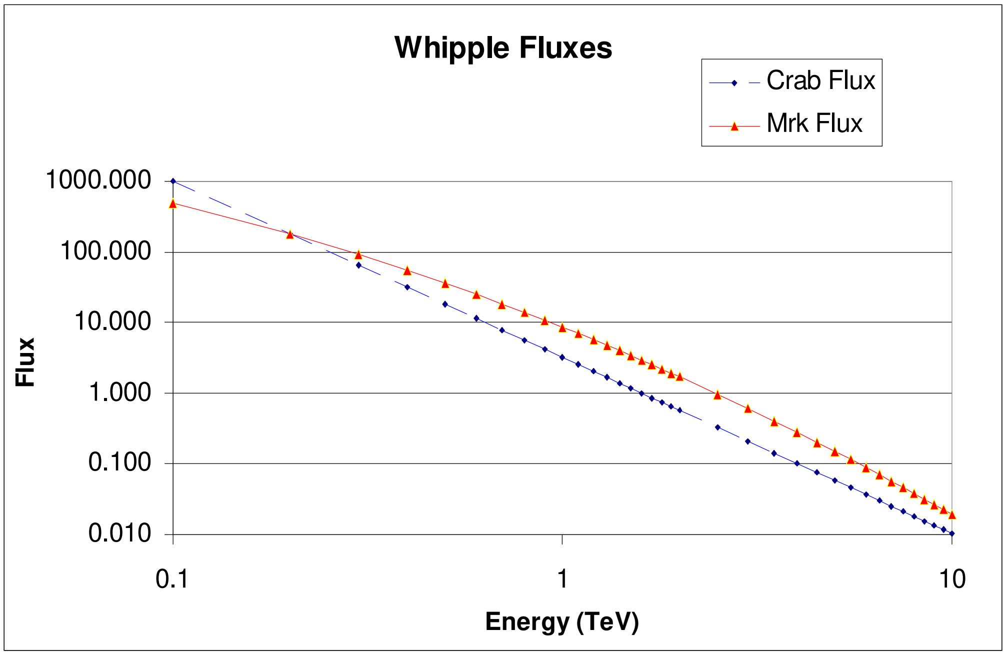
$$\Phi_H = (9.7\pm0.3\pm2.0) \times 10^{-7} (E/1\mathrm{Tev})^{-(1.9\pm0.05\pm0.05)} \exp[-E/(5.7\pm1.1\pm0.6)]\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}.$$

Unfortunately, these two groups parameterize the flux differently so it is difficult to compare them, except to see that they agree at 1 TeV. The figure below shows the two spectra.



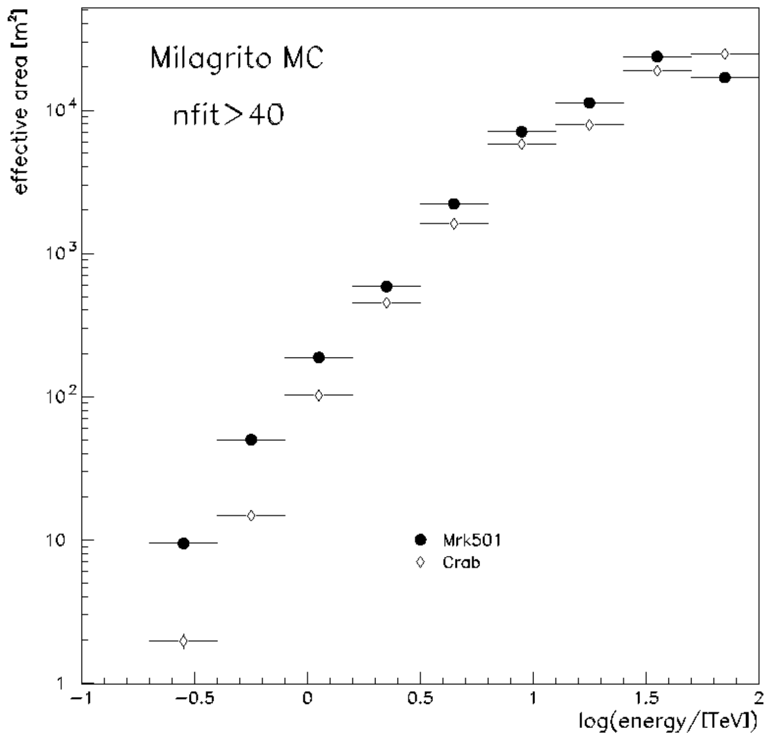
Note that the two fluxes agree extremely well both in shape and in magnitude. The Whipple flux is a little bit more curved, but clearly the two groups agree that the spectral shape is not a simple power law. This has important ramifications, as discussed below. The two fluxes also agree in absolute magnitude, which is a surprise considering they are looking at different times. Nevertheless, it is clear that Whipple and HEGRA derive the <u>same flux</u> for Markarian 501 in 1997. It is important to remember that Whipple measures photons above ~300 GeV while the HEGRA array measures photons above ~1.25 TeV; the Whipple points go out to 10 TeV while HEGRA goes out to 24 TeV. There is also evidence that the spectral shape is the same during flares as at times when Mrk 501 was not flaring.

The figure below shows the flux for the Crab and Markarian 501 from Whipple on the same scale. The curved spectrum for Markarian implies that the measured ratio (Mrk/Crab) of the rates of detected gamma rays and of the integral spectra should depend on the energy threshold.



We see from the above that there may be a way to reconcile the claims that "Whipple saw Markarian 501 at 1.4 times the Crab" and "HEGRA saw Markarian 501 at 3 times the Crab." To quantify this, one needs to know the effective area vs. energy for the instruments and then convolve them with the measured spectra. Both Whipple and HEGRA give their effective area vs. energy in publications, but the areas are functions of the zenith angle (as it is for Milagro). To do this right, one would need to convolve the effective area as a function of zenith angle with the actual zenith angles of their observations; this is something that I can only approximate. When I do this, I find that Whipple should see a gamma rate for Markarian 501 that is ~2.0 times the rate from the Crab, while the HEGRA array should see a rate 2.7 times the rate from the Crab. Qualitatively I clearly expect HEGRA to see a larger ratio. Similarly I find that the HEGRA CT1 and CT2 telescopes should see a ratio of ~2.8 (they claim ~3). The units in the Table above are effective Crab units as detected by Whipple; the other ACTs are appropriately renormalized when necessary.

Now of course the $64 question is what do we expect for Milagrito? Stefan calculated the Milagrito effective area vs. energy for photon events with NFIT>40, (*i. e.* events that are reconstructed by the fitter) with the Monte Carlo. The plot below shows the effective area for a Crab source day and for a Markarian 501 source day.



Convolving these with the measured fluxes, I find that we expect to observe 4.1 times more events from Markarian 501 than from the Crab in Milagrito! Remember that the plot in Stefan's Paris paper indicated that the expected significance for Markarian should be ~1.2 times the significance for the Crab **for the same flux**. Now I'm not claiming that putting in the Whipple flux changes the relative significance from 1.2 to 4; one must fold in the angular resolution for the events from the two sources and the relative cosmic-ray rates in the source bins. However, I do believe that it is important for Stefan to recalculate the expected significance for Markarian 501 with the correct (curved) spectrum. Then we will have a better estimate of the expected relative sensitivities of Milagrito to these two sources.

There are still two problems. The first is that we have no information on the expected flux from Markarian 501 for about 4 months in late 1997 and early 1998; we also know that apart from 5 days in early March, 1998, emission from Markarian 501 was very low in spring, 1998. Thus while the Crab is a steady source, Mrk 501 is certainly not and assuming the 1997 Mrk flux for the entire Milagrito data set may be overestimating the expected signal. Perhaps we should look separately at those times that we know Mrk 501 was "hot."

The second problem is to dead-reckon the sensitivity of Milagrito. We know that Stefan calculates that we should have seen a 3σ signal from the Crab (and we do not see that). My next task is to work on the absolute sensitivity of Milagrito including all the small "dirt" effects we have neglected.