Flux Measurements by Air Cerenkov Telescopes

An air Cerenkov telescope (ACT) counts the rate of air-showers from high energy photons from a source (and from the cosmic-ray background). The question I examine here is how they turn this photon rate into a flux and an energy spectrum, drawing heavily on publications from Whipple and HEGRA. There are a number of quantities that enter into this:

1) The expected number of Cerenkov photons produced by a given shower vs. energy, zenith angle, impact parameter...
2) The telescope effective area vs. energy.
3) The telescope gain – i. e. the number of detected photoelectrons vs. the amount of Cerenkov light falling on the mirror.
4) The efficiency of selecting photon events (and rejecting cosmic ray events).

The characteristics of the Cerenkov light pool are estimated by Monte Carlo simulation. Figure 1 shows the result of such a simulation.

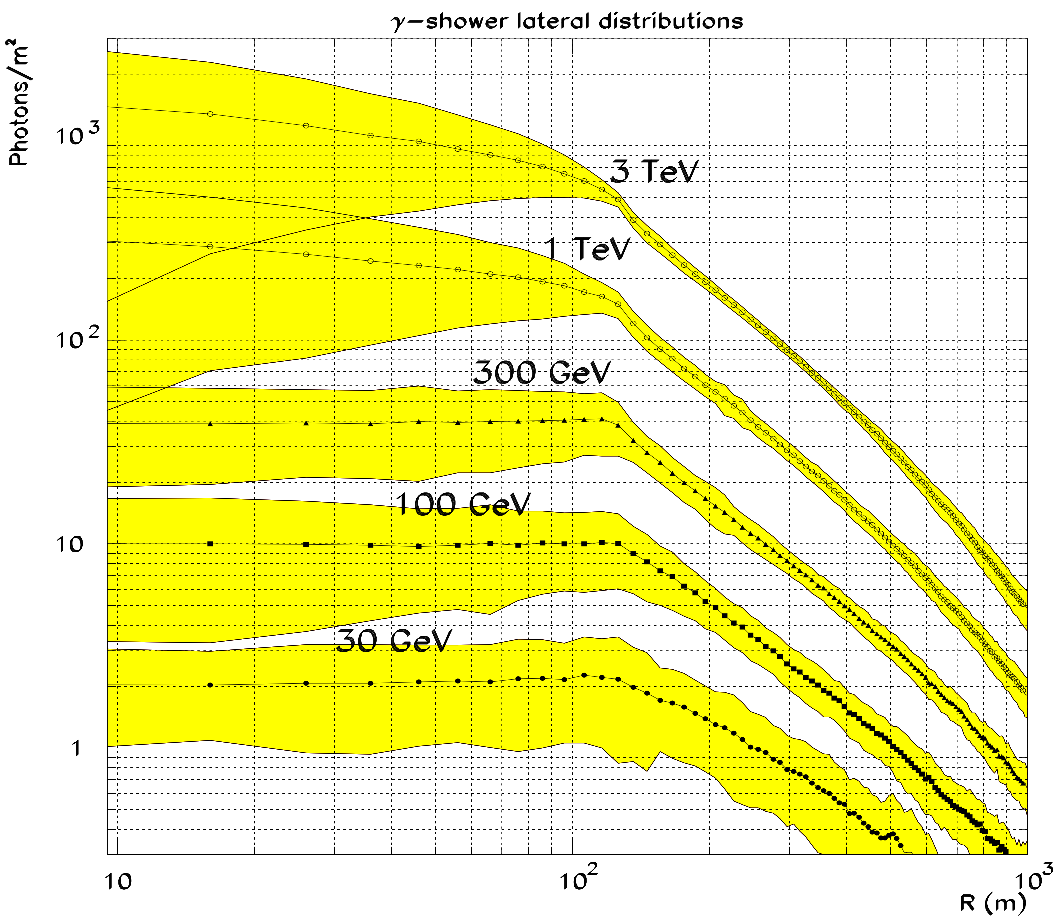

Figure 1. The density of Cerenkov photons from 300 to 600 nm as a function of R, the distance from the impact point vs. photon energy for vertical showers at an altitude of 2 km. At each energy, the mean and spread (effectively for a 1 m^2 counter) from 100 showers is shown. (from M. Punch)

Recently, the radial distribution of the Cerenkov light yield generated by gamma-ray showers has been *measured* by the 4-telescope HEGRA array (Aharonian *et. al.*, astro-ph/9807119). An array can reconstruct the shower core from the orientation of the shower images in the individual telescopes (see Konopelko *et. al.*, astro-ph/9901199). The radial shapes agree extremely well with Monte Carlo expectations.

Expected Number of Cerenkov Photons

Figure 1 shows that there are large fluctuations (~ a factor of 2) in the photon density at a given point within the light pool for photon showers at a fixed energy. These fluctuations arise from two effects:

a) Fluctuations in the longitudinal shower development (primarily the height of first interaction).
b) The sampling uncertainty for a single detector.

Simulations in which the height of the first interaction is fixed result in much smaller fluctuations (~30%) in the photon-density at a given point. In contrast, the <u>total</u> amount of light reaching the ground varies by only ~5% so that sampling the light-pool at several points (such as with the HEGRA imaging array) should reduce the uncertainty in the energy determination: HEGRA claims an energy resolution for showers coming from a fixed position in the sky of 20%. [Daum *et. al.*, Astrop. Phys. **8**, 1 (1997)]

The effects of larger zenith angles are primarily due to the increasing distance from shower maximum to telescope: the light pool is correspondingly larger but less dense. This is why the large zenith-angle technique works – at ~55°, Cangaroo reports that the mean radius of the light pool has increased to 320 m resulting in an effective collection area of 300,000 m^2. [Tanimori *et. al.* ApJ. **429**, L61 (1994)] Of course, the less-dense light pool implies that the energy threshold is increased (from 800 GeV to 7 TeV for Cangaroo).

Effective Area

The effective area for an ACT is calculated in the same way we do it for Milagro. Monte Carlo showers at a particular energy are thrown randomly over a large area (typically a radius of 250m) and the number of showers passing triggering and analysis cuts is recorded. The effective area is then the throw area times the fraction of throws that pass the cuts. A plot of effective area for Whipple is shown in Figure 6 of G. Mohanty *et. al.* Astrop. Phys. **9,** 15 (1998). Qualitatively it rises at low energies and is reasonably flat up to several x 10^4 m^2 and then gradually falls off: of course the area is larger at higher energies. For a single imaging telescope, a cut on the *distance* parameter shower image is made selecting events from 40m to 125m to the detector, where the Cerenkov light density is closely related to the photon energy; *distance* is the length between the center of the image and the center of the telescope field of view (see Figure 1 of Mohanty *et. al.*). For the HEGRA imaging array, the superior core resolution (~6m up to 120m from the core) allows cuts on the area to be made.

Telescope Gain

The telescope gain, which relates the energy of the primary gamma-ray to the size (# PEs) of the image. Two methods were used by Whipple to determine the gain:

a) Method 1, in which direct measurements of the telescope characteristics are used, whenever possible.
b) Method 2, in which the measured cosmic-ray trigger rate is compared to a calculated trigger rate using the measured cosmic-ray flux and a Monte Carlo simulation of the response to cosmic rays.

Method 1 is relatively straightforward, but the result depends upon several measurements and (unknown) atmospheric transmission. Method 2 has the advantage that it requires only a single measurement (the background trigger rate) but it relies on correctly simulating hadronic air showers and on direct measurements of the cosmic-ray fluxes and spectra.

Method 1

The mirror reflectivity is directly measured, but it degrades over time. Thus some extrapolation of performance must be made. The PMT quantum efficiency was directly measured for a few PMTs. An absolute measurement of the 1988-9 Whipple electronics gain was made by Kwok (Ph. D. Thesis - 1989) to be 1.15 ± 0.15 PE/ADC count. This utilized measurements of the PMT gain using an LED, and comparing signal size with and without the long signal cables. Another measurement in 1995 gave 1.05 ± 0.10 PE/ADC count.

Method 2

This telescope calibration uses simulated hadronic showers, the assumed atmospheric light transmission and the measured mirror reflectivity and PMT quantum efficiency; the PE/ADC is left as a free variable. The simulated and measured size (rather than energy) spectra are compared. This clearly depends upon the knowledge of the proton and helium fluxes – in the appropriate energy range there is an overall uncertainty of ~16%. The best agreement for the 1988 conditions is obtained with a gain factor of 1.33 ± 0.18 PE/ADC count including the systematic error. I should add that they use both KASCADE and MOCCA92 and the results are consistent.

These two results are in reasonable agreement with each other. Recently, calibrations have also been done using muon rings. The result for Whipple is 1.25 ± 0.13 PE/ADC for 1995 [Rovero *et. al.*, Astrop. Phys. **5**, 27 (1996)]. While this is not in disagreement with the direct measurements, it does probe a somewhat different wavelength region.

Event Selection

Two different method for event selection were used by Whipple: “extended supercuts” and a cluster analysis on the image. I won’t go into details here, but simulations indicate that both methods should retain nearly all of the gamma-ray showers that triggered the telescope. The HEGRA array does even better due to the several independent shower images.

Flux Determination

We almost have everything we need to determine a flux from the measurements. What is missing is the energy scale. A single telescope measures the shower *size* – the total number of PEs for an event, which is translated into the number of Cerenkov photons. The determination of the number of Cerenkov photons for showers of a given energy and zenith angle uses simulations and is parameterized as a function of both *size* and *distance*. The resulting energy determination has a resolution in $\ln(E_{true} / E_{meas})$ of 36% (rms).

The flux is determined assuming a spectral shape of the form:

$$dN/dE = \alpha\, (E/1\ \text{TeV})^{-\gamma}\ .$$

In Method 1, the events are binned in the estimated energy for each event (actually this is done for on-source minus off-source). The expected number of events in each bin is calculated (including the effective area vs. energy) allowing α and γ to vary. Finally the binned data are fit to the expected number of events via a chi-squared to find the best values of α and γ. This method has the disadvantage that the flux depends upon an assumed spectral shape. In Method 2, both data and simulated showers are binned by ln(*size*) and the input energy spectrum of the Monte Carlo is adjusted to get agreement.

The two methods give consistent results, given below, with α given in units of $10^{-7}\ m^{-2}\ s^{-1}\ TeV^{-1}$. The errors are statistical errors only.

Data Set; Method	α	γ
1988-9, Method 1	3.41 ± 0.25	2.38 ± 0.10
1988-9, Method 2	3.30 ± 0.25	2.60 ± 0.13
1995-6, Method 2	3.12 ± 0.25	2.38 ± 0.10

For a single telescope, HEGRA compares the integral event rate above the telescope “threshold” (actually the energy at the peak of the event rate) with Monte Carlo expectations. The flux is relatively insensitive to the assume spectral index. For the array of telescopes HEGRA constructs directly the differential photon flux using their excellent energy resolution and the effective area (as a function of energy) from simulation. They quote a systematic uncertainty of 15% in the energy scale (coming primarily from uncertainties in the atmospheric absorption and the PE to ADC conversion), which leads to a systematic uncertainty of 35% in the flux amplitude: they also quote a systematic uncertainty in the spectral index of 0.1 due to “the Monte Carlo dependence of the results.”

Discussion

We now need to examine the systematic uncertainty in the measured flux. With a steeply falling spectrum, any uncertainty in energy can be compensated by changing the flux, and vice versa. The translation of shower photons to PEs (the overall gain) is not perfectly known for ACTs. Changes in the overall gain shrink or stretch the energy scale and so should change α but not γ. However, γ could also be changed by second-order effects.

Errors in the overall gain for Whipple include:

PMT gain	10%
Electronics gain	5%

Reflectivity	10%
Atmospheric effects	5%
Total	16%

The Whipple group believes these are the dominant systematic errors. They result in systematic errors in α ($\pm$ 0.6) and in γ ($\pm$ 0.04). Of course, there may be additional unknown errors in the Monte Carlo simulations.

For a single telescope, HEGRA claims an uncertainty of 15% in the scaling from Cerenkov photons to ADC counts (this includes atmospheric uncertainties), and ~30% for uncertainties in the cut efficiencies (remember that these are smaller telescopes than Whipple). However, they changed a published value of the Crab flux measured by CT2 by nearly a factor of two because of "a smaller factor for the conversion from photoelectrons to ADC counts and including imperfections of the telescope optics in the Monte Carlo simulation."

As stated above, HEGRA quotes systematic uncertainties of 35% in α and 0.1 γ for the stereo observations.

Hillas *et. al.* (ApJ. **503**, 744 [1998]) suggests using *integral fluxes* rather than differential fluxes to compare results between groups. This reduces the dependence on the true form of the energy spectrum, and correlations in the determination of α and γ. The resulting integral flux from Whipple (combining 1998-9 and 1995-6 data) is:

$$I(> 1\text{TeV}) = (2.1 \pm 0.2 \pm 0.3) \times 10^{-7}\ \text{m}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1}.$$

Hillas *et. al.* note that the flux extrapolated back to GeV energies is an order of magnitude higher than fluxes measured by EGRET. They then give a fit to a non-power law that links up with EGRET which gives lower fluxes above a few TeV.

Other measured integral fluxes for the Crab are:

Group	Integral Flux	Above	Year
HEGRA (CT2)	$(1.5 \pm 0.2 +1/-0.5) \times 10^{-7}$	1 TeV	1994-5
HEGRA (CT1)	$(2.33 \pm 0.04 \pm 0.7) \times 10^{-7}$	1.5 TeV	1997
CAT	$(1.6 \pm 0.2 \pm ?) \times 10^{-7}$	1 TeV	1996-7
Cangaroo	$(1.3 \pm 0.2 \pm 0.8) \times 10^{-9}$	7 TeV	1992,3,6

The paper of Hillas *et. al.* shows a plot of much of this data, indicating general consistency. Note, however, that uncertainties in γ can affect the expected signal for Milagrito/Milagro, especially for data from Whipple which are primarily below 1 TeV. The best quoted flux, from Whipple, has a statistical error of 10% and a systematic error of 16%; other groups quote larger systematic errors. By eye, the agreement in the data appears to be within ~30%. The HEGRA array has not yet given a result for the Crab flux.

It is not clear to me whether any of the simulations of gamma-ray showers include an photoproduction of hadrons: articles I have looked at seem to imply that they do not. This would lead to a systematic error as some fraction of photon-induced showers would be cut by image analysis, while Milagro/Milagrito is relatively insensitive to this effect (until we incorporate some form of hadron rejection). The cross section for $\gamma p \rightarrow$ hadrons is expected to be ~ 250 μb around 1 TeV (900 μb for nitrogen assuming an $A^{2/3}$ dependence), while the pair production cross section is 20 mb for hydrogen and 474 mb for nitrogen (Tsai, Rev. Mod. Phys. **46**, 815 [1974]). Thus there is only a 0.5% probability that the first interaction produces hadrons (and a smaller probability that it produces a muon pair), but there are many chances for high energy photons to produce hadrons in the shower. My recollection is that roughly 10% of photon-induced showers look like hadron-induced showers, which seems reasonable.

Conclusion

Air Cerenkov telescopes measure roughly consistent values of the gamma-ray flux from the Crab. The statistical errors are quite a bit smaller than the systematic errors. The systematic error in the integral flux above 1 TeV is probably ~30%, although there are some unknown systematic errors in common for all ACT measurements (atmospheric absorption of Cerenkov photons, physics in Monte Carlo simulations, …). Note that the uncertainty that is appropriate to simulating Milagrito/Milagro may be somewhat larger due to uncertainties in the spectral shape.

Many of the systematic errors in the ACT fluxes would be expected to cancel when comparing the flux between two sources (such as Mrk 501 and the Crab). This is the next thing I will study.