Observations of TeV Photons at the Whipple Observatory

R. C. Lamb,[1] C. W. Akerlof,[2] M. F. Cawley,[3] E. Colombo,[4] D. J. Fegan,[5] A. M. Hillas,[6]
P. W. Kwok,[4] M.J.Lang,[4] D. A. Lewis,[1] D. J. Macomb,[1] D. I. Meyer,[2] K. S. O'Flaherty,[5]
P.T.Reynolds,[4] G. Vacanti,[1] and T.C.Weekes[4]
[1]Iowa State University, Ames, IA 50011 USA
[2]University of Michigan, Ann Arbor, MI 48109 USA
[3]St. Patrick's College, Maynooth, Co. Kildare, IRELAND
[4]Harvard-Smithsonian Center for Astrophysics, P.O. Box 97, Amado, Arizona 85645 USA
[5]University College, Dublin, IRELAND
[6]University of Leeds, Leeds, UK

Abstract

The Whipple Observatory 10 m gamma-ray telescope has been used to search for TeV gamma-ray emission from a number of objects. This paper reports observations of six galactic and three extragalactic objects using the Cherenkov image technique. With the introduction of a high-resolution camera (1/4° pixel) in 1988, the Crab Nebula was detected at a significance level of 20 σ in 30 hours of on-source observation. Upper limits at a fraction of the Crab flux are set for most of the other objects, based on the absence of any significant dc excess or periodic effect when an *a priori* Monte Carlo determined imaging selection criterion (the "azwidth cut") is employed. There are weak indications that one source, Hercules X-1, may be an episodic emitter. The Whipple detection system will be improved shortly with the addition of a second reflector 11 m in diameter (GRANITE) for stereoscopic viewing of showers. The combination of the two-reflector system should have a signal-to-noise advantage of 10^3 over a simple nonimaging Cherenkov receiver.

1. INTRODUCTION

At the 1977 Frascati Conference on gamma-ray astronomy, Weekes and Turver[1] proposed "the use of two parallel large reflectors each equipped with multiple detector channels to provide two 'images' of the shower in Cherenkov light." This goal should be achieved by Fall 1991 with the installation of a second large reflector at the Whipple Observatory. The effectiveness of the imaging approach has already been verified with the present single reflector system in which the Crab Nebula has now been detected at a significance of 20 σ.

This paper summarizes results for all sources observed with the Whipple observatory gamma-ray telescope and benefits from individual presentations, at this meeting, of specific sources by members of the collaboration: M. F. Cawley (1E2259+586), E. Colombo (PSR 0355+54), D. J. Fegan (Cygnus X-3), D. A. Lewis (4U0115+63), P. T. Reynolds (Hercules X-1) and T. C. Weekes (Crab Nebula). Expected improvements in sensitivity when a second reflector (GRANITE) comes online are also briefly discussed.

2. THE CHERENKOV IMAGING TECHNIQUE

The sensitivity of ground-based gamma-ray detection systems is, at the present time, limited by their ability to distinguish gamma-ray induced air showers from cosmic ray background showers. A typical Cherenkov receiver has an effective collection area of 5×10^8 cm^2 for gamma-ray induced air showers with a somewhat smaller collection area for cosmic-ray showers. Thus a gamma-ray source with a flux of 10^{-11} photons/cm^2/s above 1 Tev will produce 50 showers in a 10^4 second observation. (The intensity of this source is approximately 0.5 that of the Crab Nebula.) If the effective angular resolution of the detector is 1^0 (radius), then during this same interval approximately 10^3 as many background showers will be registered. With no discrimination against the background, a total observation time of 10^7 seconds would be required (1/2 time on-source, 1/2 time off-source) to detect the source with a significance of 5 σ.

It is therefore obvious that some form of *strong background rejection* must be utilized if gamma ray sources of this intensity are to be observed and studied reliably. Although the need for dramatic improvements in sensitivity has long been recognized, progress has been slow. A number of different approaches have been proposed, each based on possible differences between gamma-ray and cosmic-ray induced air showers. Simulations (Hillas 1985[2], Plyasheshnikov and Bignami 1985[3], Macomb and Lamb 1990[4]) are now in agreement that, over the energy range 0.1 to 10 TeV, both the lateral distribution of Cherenkov light and the shape of images are substantially different between gamma rays and cosmic rays. The image differences have been observationally verified with the Whipple Observatory's instrument; however the predicted differences in the lateral distributions remain largely untested. Small differences in the spectral content and the time profile of the light may also be expected from simple arguments based on the presence of a penetrating muon component for cosmic ray showers.

Some appreciation of the differences that exist between gamma-ray and cosmic-ray images may be gained by looking at the Cherenkov light pattern for a typical 1 TeV shower of each type. Fig. 1 illustrates some of these differences. What is shown is the pattern of light in a hypothetical image plane with perfect angular resolution. In each case the shower is directed vertically, with an impact parameter relative to the detector of 80 meters. The much greater transverse momentum of the nucleon cascade produces wider Cherenkov images and occasional arcs of light corresponding to local muons. Because the photon's radiation length is only about 1/3 the nucleon's interaction length, fluctuations in the image characteristics from shower-to-shower are much less severe for gamma-ray showers than those from cosmic rays.

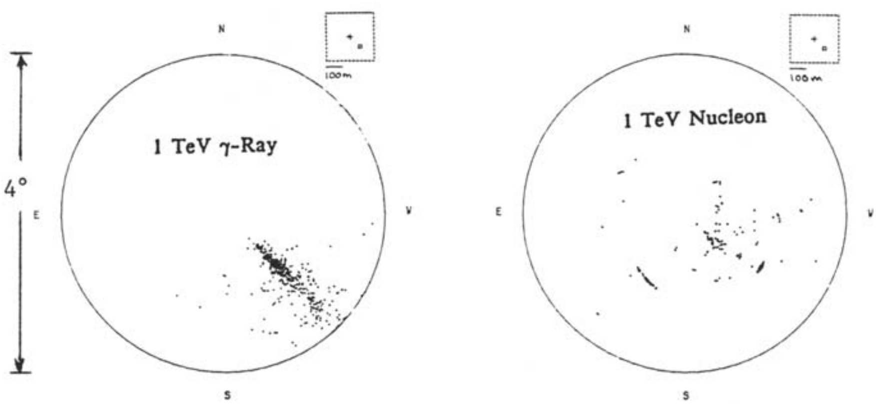

Fig. 1. Monte Carlo simulations of the pattern of the Cherenkov light as viewed by an imaging detector with no aberrations. In each case the source direction is the center of the field-of-view. The detector is pointed in this direction and the detector itself is located 80 meters from the core of the shower as indicated by the small box in which the core's location is shown as a "+" and the detector as a "□".

Since 1982 the Whipple Observatory gamma-ray effort, based on a single 10 meter reflector, has been directed toward imaging. Initial operation with a camera consisting of 19 photomultipliers, with a separation of $1/2^0$, verified that imaging of the Cherenkov light of individual air showers was feasible. Within a short time the camera was expanded to 37 elements. Observations with the 37 element camera culminated with a 9σ detection of the Crab Nebula (Weekes *et al.* 1989[5]). In 1988 a high resolution camera (109 elements, $1/4^0$ pixel spacing) was installed (Cawley *et al.* 1990[6]), which has given a further gain in sensitivity corresponding to a signal-to-background improvement of more than a factor of 100 compared with a detector with no background rejection ability. With the addition of a second reflector 120 meters distant (GRANITE), information on the lateral distribution of the light will also be obtained. It is expected that the resulting stereoscopic viewing of showers will lead to a signal-to-background of at least a factor of 10^3 better than a nonimaging detector.

The image analysis technique employed by the Whipple Observatory is based on a moments calculation of the pattern of light for each shower (Hillas 1985[3], Weekes *et al.* 1989[5]). Fig. 2 illustrates the definition of the principal parameters: Width, Length, Miss, and Azwidth. Simulations show that these parameters are somewhat dependent on the impact parameter of the shower. A rough measure of the impact parameter is the location of the phototube which contains the largest signal. Fig. 3 shows the configuration of the phototubes currently in use, showing concentric hexagons which define "zones" of approximately equivalent phototubes. In fig. 4 the distribution of azwidth for zones 1 through 5 is shown for simulated gamma-ray and proton showers. The dashed line gives an optimum cut value to be used in order to maximize the significance of any signal. A comparison between simulated proton showers and actual background data is shown in fig. 5 for each of the shower parameters. Good agreement between simulations and actual performance is seen.

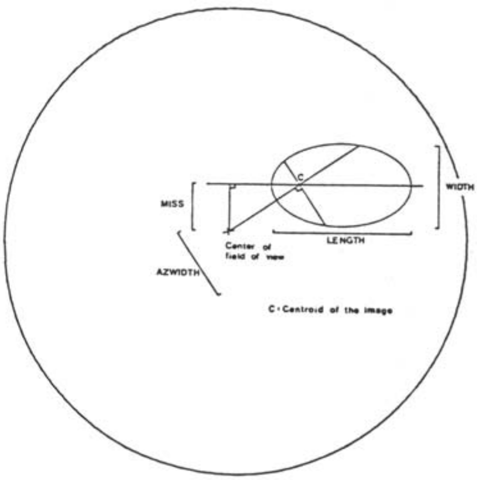

Fig. 2. Definition of image parameters.

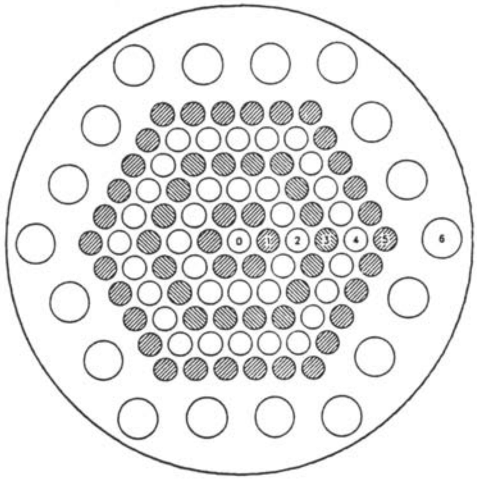

Fig. 3. The layout of the photomultipliers in the focal plane of the reflector. The inner pixel spacing is 0.25°. The numbers refer to the zones, the convention used to designate the position of the images relative to the center of the camera.

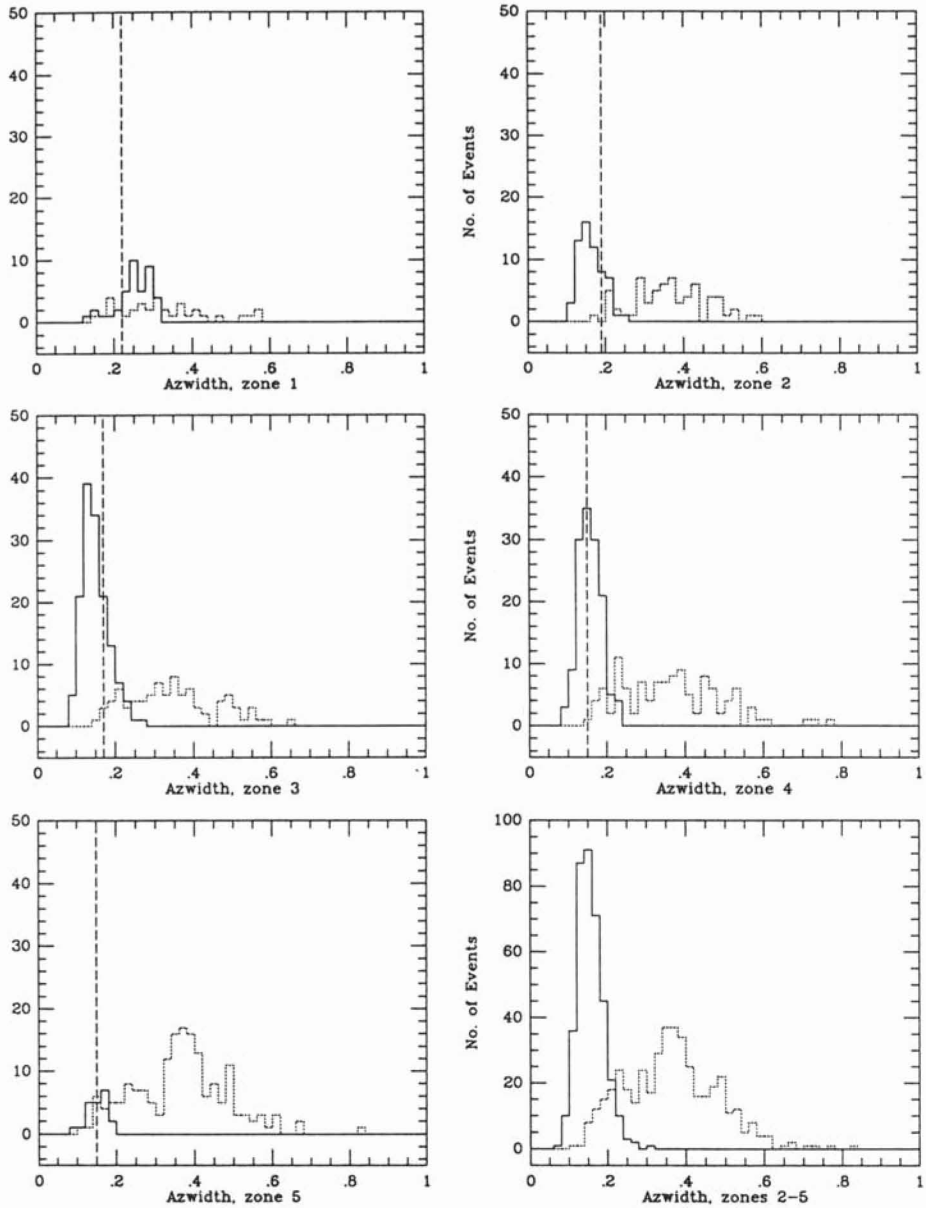

Fig. 4. Simulations of distributions of the Azwidth parameter by zone for gamma-ray and proton primaries. The gamma-ray domains are to the left of the dotted line.

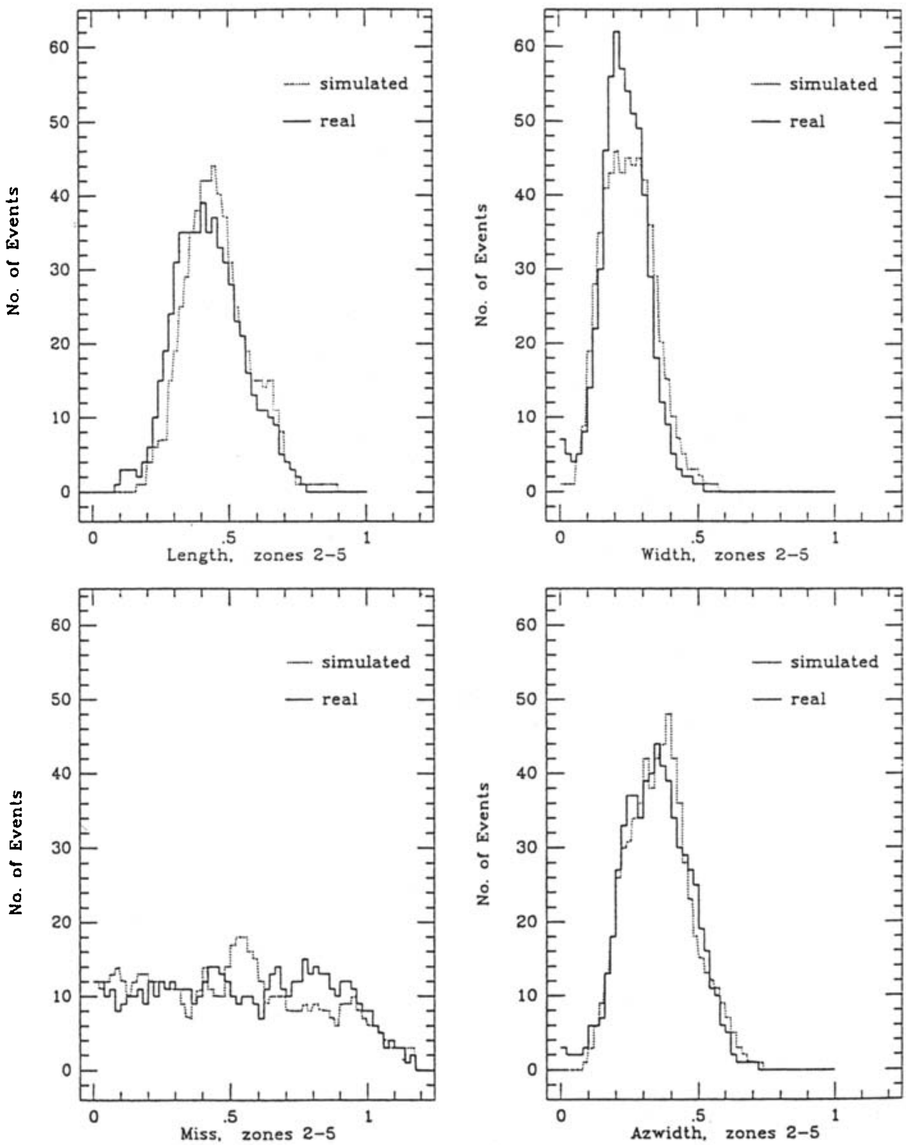

Fig. 5. Simulations and measurements of background for four parameters: Length, Width, Miss, and Azwidth for the high resolution camera directed at the zenith. Only zones 2–5 are included.

3. OBSERVATIONS

Table 1. Galactic sources observed

Source	Observ. Period	Total Hrs. On-Source	Significance
Crab Nebula	1988-89	30	20 σ
Hercules X-1	1984-89	445	No signal with imaging
4U0115+63	1985-88	124	No signal with imaging
1E2259+586	1985-88	80	No signal with imaging
Cygnus X-3	1988-89	36	No signal with imaging
PSR 0355+54	1989	25	No signal with imaging

3.1 Crab Nebula

The $1/4^0$ pixel camera was used to observe the Crab Nebula between November 1988 and March 1989 and preliminary reports on these observations have been presented elsewhere (Lang et al. 1990a,[7] Lang et al. 1990b[8]) with a final report recently submitted (Vacanti et al. 1991[9]).

A total of 65 ON/OFF run pairs passed objectively imposed selection criteria: zenith angle less than 35^0, sky quality excellent, and absence of instrumental problems. Table II lists the total number of showers taken on-source and off-source, with various levels of selection. "Raw" data correspond to all events that triggered the camera. After pedestal subtraction and gain adjustment, the events were subjected to a low-level filter. Those that passed constitute the "Filtered" events. The filter criteria eliminates zone 1 and 6 events, as well as rejecting events in which only two photomultipliers have a signal (likely to be direct cosmic ray hits on the tubes). The "Azwidth" cut events are those that survive the azwidth cut described above. The significance of the detection with the azwidth selection is 20 σ.

Table 2. Number of showers used in Crab Nebula database

Mode	Raw	Filtered	Azwidth selected
ON	499,783	383,065	14,622
OFF	494,722	378,600	11,389
Difference	+5,061	+4,465	+3,233
σ	5.1	5.1	20.0

In figure 6 the distributions of azwidth values for all on-source and all off-source observations are shown. The only significant difference between the two distributions occurs for azwidth values less than 0.2^0. This is precisely the region in which an excess is to be expected if, in fact, the Crab Nebula is a source of high energy gamma rays (cf. figure 4.) The effective collection area determined by the simulations is $4.2\text{x}10^8$ cm^2 with an effective energy threshold of 0.4 TeV. The signal thus corresponds to a flux of 7.0 ($\pm$0.4) x10^{-11} photons/cm^2/s. (The error in the flux quoted is purely statistical; as in all VHE gamma-ray experiments there is an uncertainty of a factor of 1.5 in both energy threshold and flux values.)

Energy spectrum: Simulations show that the relation between the Cherenkov light detected and the energy of the initiating primary photon is linear for showers with core distances of 50 to 125 m, corresponding to centroid values of 0.68° to 0.95°. In figure 7 the distributions of azwidth selected on-source and off-source showers with these centroid values are shown. The difference spectrum is shown in figure 7b. It is clear that the difference spectrum is from a flatter distribution than the background. The best estimate of the measured source spectrum is given by $dN/dE = 2.7\ \text{x}10^{-11}\ E^{-2.4\pm0.3}$ photons/cm^2/s/TeV, when the energy is expressed

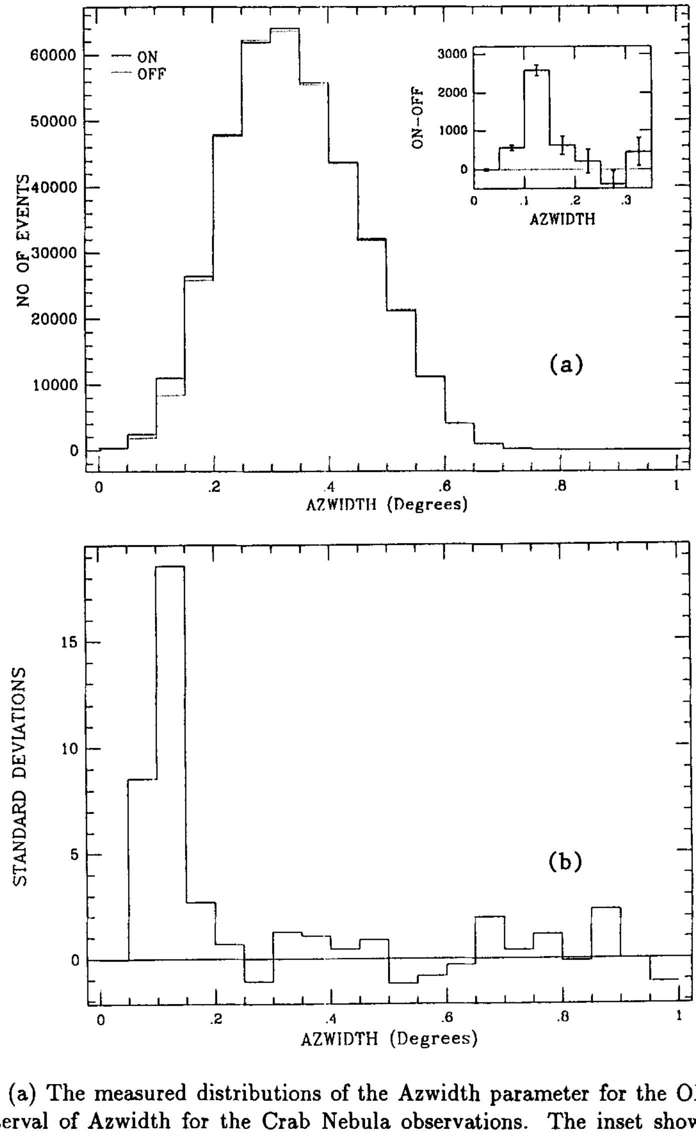

Fig. 6. (a) The measured distributions of the Azwidth parameter for the ON and OFF per 0.05° interval of Azwidth for the Crab Nebula observations. The inset shows the ON-OFF distribution. (b) The ON-OFF distribution plotted as number of standard deviations per 0.05° interval of Azwidth.

in TeV. The error in the exponent, ±0.3, is largely due to systematic uncertainties, since the formal statistical error is ±0.1.

Tests: In an effort to guard against the possibility that the signal is an artifact of the detector and/or the observing procedure, these observations have been subjected to a number of tests. We discuss three; for a complete discussion the reader is referred to Vacanti et al. (1991).[9] 1) The flux value that is obtained in these observations is consistent with the value obtained with the 0.5° pixel camera (Weekes *et al.* 1989[5]). The operating conditions for this camera were significantly different than those for the present camera, the major difference being that the earlier camera was operated with padding lamps while the present camera was not.

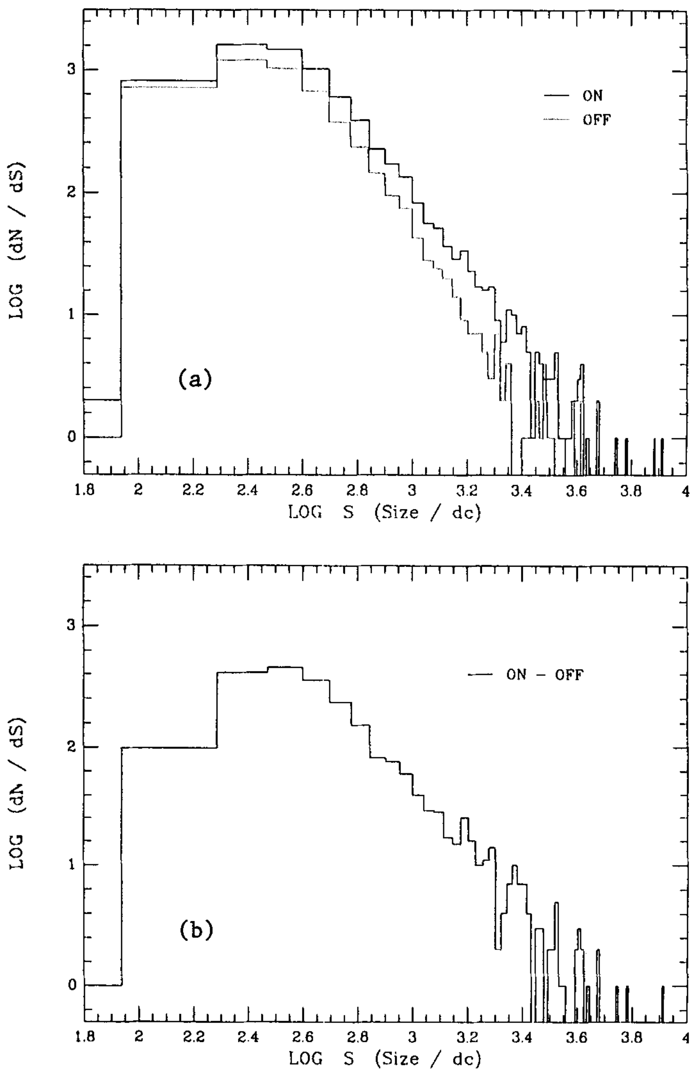

Fig. 7. (a) The measured differential image size (number of photoelectrons) spectrum for a sub-set of the 1988–89 Crab Nebula database. The bin size in 100 photoelectrons. (b) The ON-OFF differential spectrum.

2) The presence of the 3rd magnitude star, Zeta Tauri, about 1° from the Crab Nebula, has been proposed as a possible source of the excess. Although its influence on shower images is neutralized by turning off the phototubes affected by it in both on-source and off-source scans, the possibility exists that some subtle residual effect remains. To test for this possibility the camera has been divided into halves, one with the star, the other without. The net excess was found to be divided equally between the two halves, indicating that any possible bias due to the star was negligible. 3) The excess is consistent with other choices of the Hillas parameters; e.g. selections based on width, length, or miss criteria give excesses which are consistent with the expectations derived from the simulations.

Angular resolution:

The parameters used to characterize an image are of two types; those that characterize its shape such as Length and Width, and those that characterize its orientation such as Miss. Azwidth combines both properties into a single parameter. One can study the angular resolution of the detector by first applying shape selection criteria and then examining the resulting distribution of an orientation parameter. In figure 8a the on-source and off-source distributions of the Miss parameter are shown for those showers which have been shape selected, i.e., their Length and Width values fall in the gamma-ray domains of each of these parameters. The only significant difference between the two distributions, shown in figure 8b, is for the angular range less than 0.2°. Figure 8c and 8d show cumulative distributions, first in terms of the number of excess showers, and then in terms of the statistical significance of the excess.

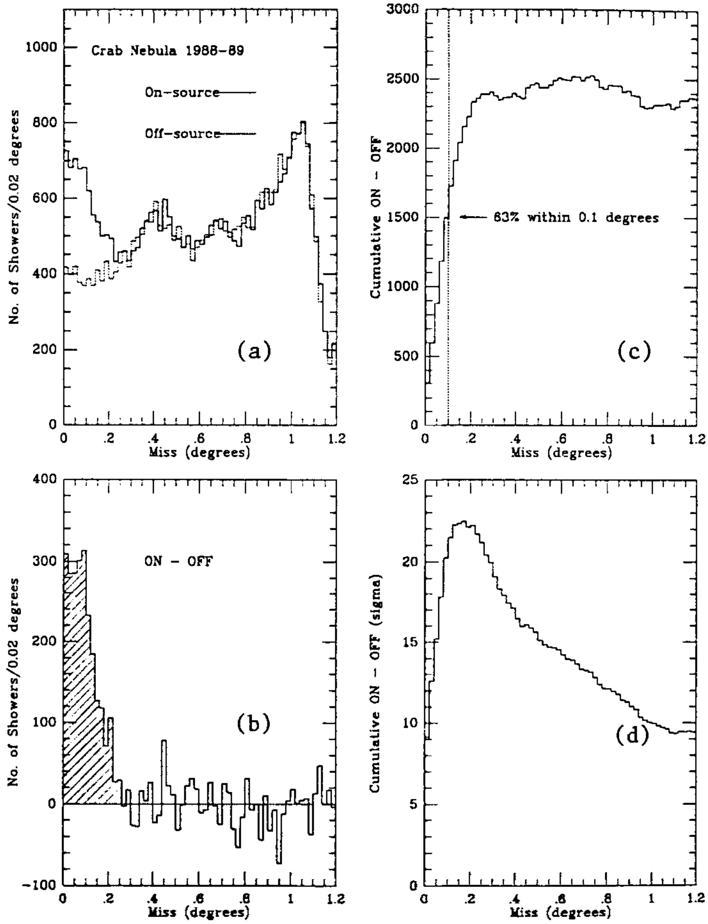

Fig. 8. The distribution of the Miss parameter for a subset of the Crab Nebula data: (a) ON and OFF distributions per 0.02 bin of Miss after preselection by Width and Length; (b) the ON-OFF distribution; (c) the cumulative ON-OFF difference; (d) the cumulative ON-OFF difference in standard deviations.

Several conclusions can be drawn from figure 8. In the first place, the combination of parameters: Length, Width, and Miss, give a result in agreement with that obtained with Azwidth. This is a further test of the reality of the signal excess. Furthermore, from the figure one has a direct measure of the angular resolution of the instrument. It is apparent that 63% of the signal comes from Miss values less than 0.1°. Finally, if either the instrument was not pointed at the Crab Nebula to an accuracy of better than 0.1° or the source of the gamma-rays was offset from the direction of the Crab by approximately the same amount, then the difference distribution would not show a clear peak near zero degrees. Since it does show such a peak one can conclude that neither of these possibilities are likely.

Pulsar limits:

The 1988-89 Crab database has been searched for evidence of periodicity associated with the pulsar, using the procedures described in Weekes *et al.* 1989[5]. No evidence is found, and a limit (at the 99% confidence level) of less than 10% pulsed emission is set.

Models:

Three models have been proposed to explain the observed TeV emission from the Crab Nebula. The salient feature of these three models and the integral spectral indices that they predict are summarized in Table 3. It is clear that the Compton models are the best fits with the spectral index reported above. For the first model the flux reported is compatible with an ambient magnetic field of 3 $\times 10^{-4}$ G. However the predictions of these simple models are not consistent with the steady flux reported at 100 MeV energies (Clear *et al.* 1987)[10]. More sophisticated models which take into account the detailed distribution of electrons and photons from recent mapping of the nebula at all wavelengths are needed to resolve this issue.

Table 3. Crab models for TeV emission

Model	Location	Mechanism	Progenitor	Target	1 TeV Index (Integral)
ref a.	Nebula	Compton	Electron	Photon	-2.2
ref b.	Pulsar	Comp/Synch	Electron	Photon	-1.8
ref c.	Nebula	π^0 decay	Proton	Nucleon	-0.3

References: [a]Gould (1964)[11]; Rieke and Weekes (1968)[12]; Grindlay and Hoffman (1971)[13]. [b]Kwok and Cheng (1990)[14]. [c]Cheng *et al.* (1990)[15].

3.2 Hercules X-1

TeV gamma-ray emission from Hercules X-1 was first reported by the University of Durham group (Dowthwaite *et al.* 1984)[16], followed by observations at 500 TeV by the Fly's Eye group (Baltrusaitis, *et al.* 1985[17]) and 1 TeV by the Whipple Observatory (Gorham *et al.* 1986)[18]. A paper summarizing the Whipple Observations of Hercules X-1 from 1984-1990 is in preparation (Reynolds *et al.* 1991)[19]; here we summarize observations through 1989, totalling 445 hours on-source. A break-down of these observations according to the type of camera and the conclusions regarding the statistical strength of any possible signal is shown in Table 4.

Table 4. Whipple Observations of Hercules X-1 1984-89

Observ. Interval	Type Camera	On-source Time	Uncut Result	Azwidth Selected
1984-87	1/2° pixel	265 h	1% chance signal	no signal
1988-89	1/4° pixel	180 h	no signal	no signal

We will discuss the possible signal which is seen in the 84-87 dataset shortly. However a strong conclusion can be drawn immediately from the entries in the last column of the table. When the azwidth selection is made, there is no indication of any TeV gamma-rays coming from Hercules X-1. *Thus the Whipple Observatory has no evidence that Hercules X-1 is a source of TeV gamma rays.*

We now proceed to discuss the possibility that Hercules X-1 is an episodic emitter of signals which are other than gamma-rays, first by considering only the Whipple data from 1984-87, and then by considering the set of 1986 observations by the Whipple group (Lamb *et al.* 1988)[20], the Haleakala group (Resvanis *et al.* 1988)[21], and the CYGNUS collaboration (Dingus *et al.* 1988)[22]

The 1984-87 Hercules X-1 observations by the Whipple Collaboration have been discussed previously at conferences (Reynolds *et al.* 1990[23], Reynolds *et al.* 1990[24]). The analysis procedure adopted was based upon previous reports of episodic emission typically less than 1 hour duration. The dataset was divided into 578 non-overlapping segments of approximately 30 minutes duration, and each segment was Fourier transformed over the frequency interval 1/3 to 2 Hz. This interval, which corresponds to 3000 independent Fourier frequencies (IFF), encompasses both the fundamental (0.8079 Hz) and the second harmonic of the neutron star's spin frequency.

When this analysis is performed using all of the showers, without regard for the imaging information, then there appears to be some possible significant signal at the spin frequency of the neutron star. Several slightly different types of analysis have been performed (cf Ref. 25 and 26) all of which give a chance probability of 1% or slightly less. Figure 9 illustrates the results of one of these tests. This figure is obtained by forming the distribution with frequency of all segments which have Rayleigh power values greater than 3 in non-overlapping frequency intervals of 2 IFF. The frequency intervals are chosen so that in the vicinity of the neutron star spin frequency it is centered in an interval. The ordinate of Figure 9 is the chance probability calculated on the basis of the Fisher test (cf Lewis 1989)[25]. The highest peak in the plot occurs at the neutron star spin frequency.

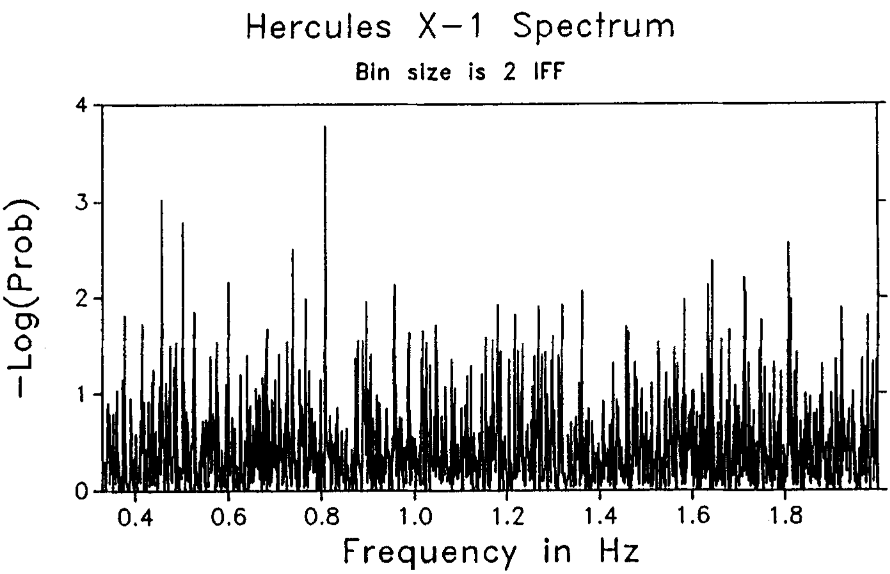

Fig. 9. The full spectrum from 0.33 to 2.0 Hz for the 1984–87 observations of Hercules X-1 is shown above. The ordinate is $-\text{Log}_e$ of the probability of obtaining, by chance, a value of the Fisher statistic equal to or greater than that measured. The largest peak occurs exactly at the X-ray pulsar frequency.

In order to assign an overall significance to the effect, all degrees of freedom must be taken into consideration. A factor of 2 comes from the fact that both the fundamental and the second harmonic were searched, and a further factor of 13 comes from the choice of a power value of 3, rather some other choice. This penalty may seem excessive, but this choice does, in fact, "optimize" the result. The overall chance probability then is 0.8%. If one adopts the point-of-view that this constitutes evidence for a signal, then the fact that when the gamma-ray azwidth cut is applied the signal vanishes, leads to the conclusion that the signal is not predominately gamma rays. The fact that when an improved camera with pixel spacing better matched to the smaller gamma ray images, produces no signals, either cut or uncut, could be consistent with this interpretation.

We now turn to a discussion of the 1986 observations of Hercules X-1 in which three groups apparently observed the same anomalous frequency, which was 0.16% higher than the neutron star spin frequency. In table 5, the three observations are summarized.

Table 5. 1986 Observations of Hercules X-1 at an anomalous frequency

Observatory (Ref.)	Energy	Frequency	Reported Prob.	Prob.(including dc excess)
Haleakala (20)	1 TeV	0.80911	0.7×10^{-2}	0.7×10^{-2}
Whipple (21)	1 TeV	0.8092	0.9×10^{-2}	0.3×10^{-2}
Los Alamos (22)	100 TeV	0.80927	0.2×10^{-4}	0.2×10^{-3}

What is the overall significance of these three detections? If we treat them simply as three independent tests of the same (no-signal) hypothesis, then they can be combined using Fisher's test as described by Eadie *et al.* (1971)[26]. This test does not make use of the information that all frequencies were the same and therefor it tends to overestimate the chance probability; the *ad hoc* nature of the search range used by all three groups (±0.3%) tends to increase it. An implicit assumption is that Hercules X-1 was not being observed by any other groups in 1986 using detectors of comparable sensitivity, so that the three observations consititue the total set of observations of this source. Unreported nondetections make it difficult to assess the overall significance, but would in general decrease the significance. If we restrict our attention only to 1986 (*a posteriori*), and assume there are no significant nondetections during this interval, the chance probability is calculated to be less than 10^{-6}. Taken at face value it would appear that Hercules X-1 was a source of TeV/100TeV emissions in May-July 1986. However, *a posteriori* probabilities are dangerous and are best treated as a hypothesis for further tests. As time continues with no confirmation of this anomalous frequency (Gupta *et al.* 1990[27] notwithstanding) then the impact of this combination of observations becomes weaker.

Two of the three detectors have the capability to distinguish gamma-ray showers from background, the Whipple detector by virtue of the image characteristics of the Cherenkov light and the Los Alamos detector by virtue of the muon content of the showers. In both cases the apparent signals do not behave as expected of gamma rays. This has led to some speculation of "new physics" which would involve a neutral, low-mass, long-lived particle (less than 2 MeV from the Whipple result; less than 60 MeV for the Los Alamos result) which is responsible for the "signals". However in view of the startling implications of this conclusion, we prefer to wait for confirmatory evidence from better instruments.

3.3 4U0115+63

4U0115+63 is a recurring transient X-ray binary with a 3.6 s pulsar in a 24 day orbit. It was first indentified by the Durham group at TeV energies in 1984 (Chadwick *et al.* 1985)[28] by virtue of its characteristic periodicity. Lamb and Weekes (1986)[29] associated it with the transient TeV gamma-ray source Cas γ-1 discovered by Stepanian *et al.* (1975)[30].

The Whipple observations of 4U0115+63 were taken from 1985 through 1988 with both the medium resolution camera and the present high resolution camera. The database consists of observations from 60 nights with excellent weather with 123.5 hours of on-source data. A subset of the observations were taken in the comparison mode in which both on-source and off-source regions were observed. Table 6 lists the results of these observations.

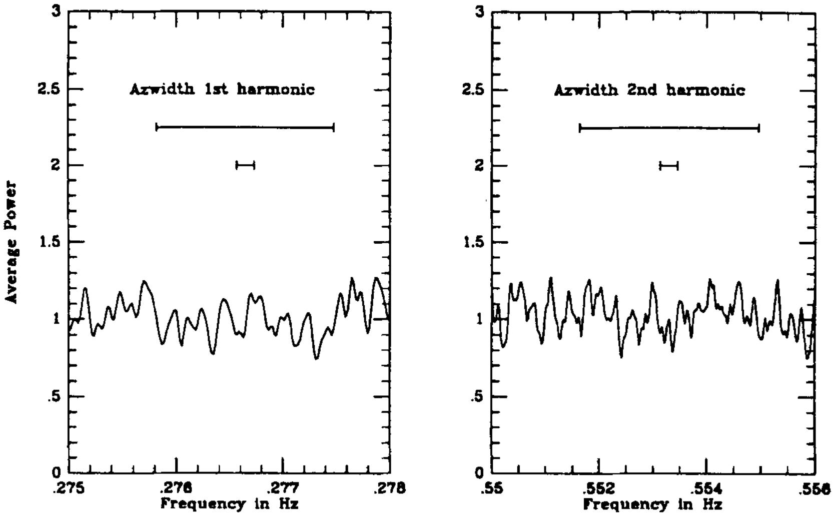

Fig. 10. Incoherent power spectra for *azwidth*-selected data for 4U0115+63. The ordinate is the average Rayleigh power in the 60 segments. Both narrow and wide signal search ranges are indicated in the figure. There is no evidence for a signal.

3.5 Cygnus X-3

D. J. Fegan (1990)[40] has recently reviewed observations above 0.3 TeV of Cygnus X-3. He concludes: "The new body of evidence...serves only to deepen rather than resolve mysteries associated with this enigmatic object." Unfortunately, the observations by the Whipple Observatory in 1988-89 with the present, high resolution camera do not help. Data were taken for 35.5 hours on-source and an equal time off-source during this period. Three types of analyses were performed: a search for steady emission using the ON/OFF comparison, a search for the 4.8 hour modulation, and a search for the 12.59 ms periodicity reported by the Durham group (Chadwick *et al.*1985)[41]

In table 6 the results of the on-source/off-source comparison are given. The flux upper limits are scaled to the value of the flux of the Crab Nebula.

Table 6. Cygnus X-3 ON/OFF observations. 1988-89

Type Analysis	Showers On-source	Showers Off-source	Excess	Flux limit
uncut	407,857	408,620	-0.8 σ	0.6 Crab
azwidth cut	15,480	15,537	-0.3 σ	0.3 Crab

Both the search for a 4.8 hour modulation and the search for a 12.59 ms pulsation were negative. Our search for a 12.59 ms pulsation has been confined to the phase interval 0.6425 to 0.6775 in accordance with the Durham prescription. This interval encompasses 3.3 hours of observations. It should be noted that the ms periodicity has a reported duty factor of order 10% or less which mitigates the significance of our failure to confirm.

3.6 PSR 0355+54

PSR 0355+54 is a short period (156 ms) pulsar characterized by low timing noise and occasional large timing glitches. It has been previously reported to be a TeV gamma-ray source by the Tata group (Bhat et al. 1990)[42] based on 24 hours of observations in December 1987, approximately 22 months after the last major timing glitch.

Table 6. 4U0115+63 ON/OFF observations: 1988 Dec 1 - 12

Type Analysis	Showers On-source	Showers Off-source	Excess
uncut	67,194	66,812	1.0 σ
azwidth cut	1,524	1,498	0.5 σ

The derived steady flux upper limit from these observations is 3 x10^{-11} photons/cm^2/s above 0.4 TeV, the threshold of the camera in 1988. This value corresponds to an intensity of 0.4 that of the Crab Nebula.

Most of the data were taken in the tracking mode so that a dc analysis is not appropriate. These data were subjected to Fourier analysis in a search for evidence of periodic emission. Our group has previously reported evidence for periodicity at a chance probability of 1% (Lamb *et al.* 1987)[31] was based upon an analysis which assumed source coherence over the three nights observation. A paper by Lewis, Lamb, and Biller (1991)[32] reassesses this probability to be 7%, so that Lamb *et al.* (1986)[29] should not be considered confirmation of either the Durham (Chadwick *et al.*)[28] or the Crimean (Stepanian *et al.*)[30] result.

Because of the difficulties in correctly assessing chance probabilities with highly gapped data analyzed as a single coherent time stream, each night's observation was considered to be a single coherent time series, analyzed over the frequency range of 0.2 to 0.6 Hz. This range includes both the fundamental at 0.277 Hz and the second harmonic. Two signal frequency ranges were chosen. A "broad" range of ±0.3% and a narrow range which was a tenth as large.

For each of these ranges and for both uncut and azwidth selected showers three different types of analysis were performed. In the first of these analyses, the highest power in either of the search ranges was tabulated. Since the degrees of freedom are well established, the overall chance probability of a result is readily assessed. The highest power in any of the 8 distinct power distributions (2 search ranges, 2 harmonics, and 2 choices of either uncut or azwidth-cut data) was 11.9. After multiplication by the degrees-of-freedom, an overall chance probability of 12% results so that such a high power is entirely consistent with chance. In a second type of analysis the distribution of maximum powers was examined. This type of analysis is particularly useful for episodic sources. Again no evidence for emission was seen. Finally, in a third type of analysis the power for the 60 nights was combined incoherently. Figure 10 shows the results for both the fundamental and the second harmonic for the azwidth selected showers. There is no evidence for any emission at either harmonic. An extensive paper summarizing these observations has been submitted (Macomb *et al.* 1991)[33].

3.4 1E2259+586

This nature of this 6.98 s periodic source is uncertain; perhaps it is powered by accretion, perhaps not. A recent article by Paczyński (1990)[34] explores one possibility and gives other references to the source. Evidence for TeV emission, pulsed at the second harmonic, has been reported by the Durham group (Brazier *et al.* 1990)[35] at a flux value of approximately three times that of the Crab Nebula, based on 13 hours of data spanning 8 days, October 4-11, 1988. This claim is based upon a periodic analysis in which 6 nights of observation were analyzed coherently.

The Whipple Observatory has 80 hours of observation including 13 hours during 1988 Oct 5-9 overlapping the time of the Durham observation. A paper (Cawley *et al.* 1991[36]) reporting results from these observations is in press. A number of different types of periodic analysis were performed, for both a broad frequency range of ±0.5% and a narrow range of ±0.06 %, for both the fundamental and second harmonic, and for both uncut and azwidth selected data. No evidence for emission is seen, with a flux limit of 1/8 that of the Durham group corresponding to a level of 0.4 that of the Crab Nebula. Fig. 11 shows the spectrum of this source from the X-ray region to the TeV/PeV region.

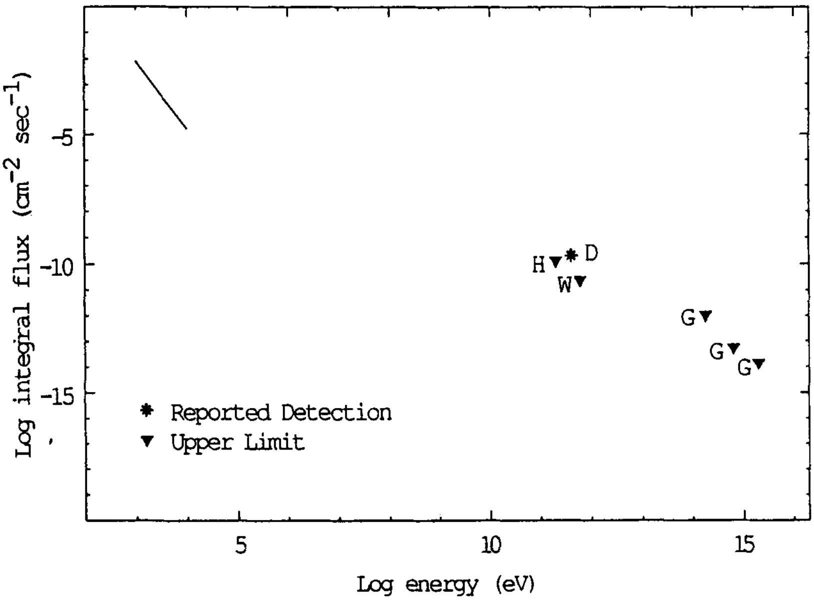

Fig. 11. Flux measurements and upper limits 1E2259+586. The continuous line indicates the high energy tail of the X-ray spectrum (Hanson *et al.* 1988[37]). H = Haleakala unpulsed limit (Weeks 1988[38]), D = Durham point (Brazier et al. 1990[35]), W = Whipple Collaboration pulsed limit (Ref. 36), G = Grex unpulsed limits (Bloomer *et al.* 1987[39]).

The Whipple group observed this source in the on-source/off-source comparison mode for a total of 24 on-source hours during September-December 1989. Two types of analyses were performed, an ON/OFF comparison and a search for periodicity. Both were negative. Table 7 gives the results of both analyses. As above the flux limits are scaled to the value of the Crab Nebula flux. The periodic limit is particularly low since there was a precise phase interval, 0.51 to 0.54, to be examined based on the Tata observation. At this meeting, Ramana Murthy for the Tata group (Acharya *et al.* 1991)[43] presented October 1989-January 1990 observations which place a nonpulsed flux upper limit of approximately 0.15 that of the Crab, in agreement with the Whipple result.

Table 7. PSR0355+54 observations. Sept-Dec 1989

Type analysis	Showers On-source	Showers Off-source	Excess	Flux limit
uncut	251,633	251,776	$-0.2\,\sigma$	0.6 Crab
azwidth cut	8,585	8,724	$-1.1\,\sigma$	0.2 Crab
periodic				0.03 Crab

3.7 Extragalactic sources

In addition to the above galactic sources, three extragalactic sources have been observed by the Whipple group, two quasars, 3C3273 and 3C279, and the active radio galaxy M87 (Virgo A). 3C273 has been reported to be a 100 MeV source (Swanenburg *et al.* 1978[44]). Table 8 gives an observational summary of these observations.

Table 8. Extragalactic sources observed 1989

Source	Type data	On-source time (h)	On-source showers	Off-source showers	Excess
3C273	uncut	10.8	145,777	146,115	-0.6 σ
"	azwidth cut	"	4,883	4,787	+1.0 σ
3C279	uncut	10.8	106,372	107,505	-2.4 σ
"	azwidth cut	"	1,905	1,960	-0.9 σ
M87	uncut	13.5	198,613	199,553	-1.5 σ
"	azwidth cut	"	3,556	3,632	-0.9 σ

The effective energy threshold of both quasars is somewhat greater than the value 0.4 TeV for the Crab observations inasmuch as these sources were observed at an average zenith angle substantially greater than the Crab. The effective threshold for 3C273 is 0.6 TeV, for 3C279 0.7 TeV. If we scale all flux limits to a common 0.4 TeV, then all 3 sources have a 95% confidence flux limit of 0.3 Crab based on the azwidth selected showers.

4.0 The Future: GRANITE

The GRANITE project expands the single reflector monocular view of showers to a fully stereoscopic view. In the fall of 1991 a second reflector, 11 m diameter, should be ready for operation. Equipped initially with a medium resolution (0.5° pixel) camera, it should have high resolution capability within the following year. This reflector, coupled with the present 10 m reflector and its high resolution camera, will provide stereoscopic views of Cherenkov images from individual showers over a baseline of 120 meters. Figure 12 shows a sketch of the Mt. Hopkins ridge with the location of both reflectors indicated. Details regarding the optical design and fabrication techniques are given in Akerlof *et al.* (1990)[45]

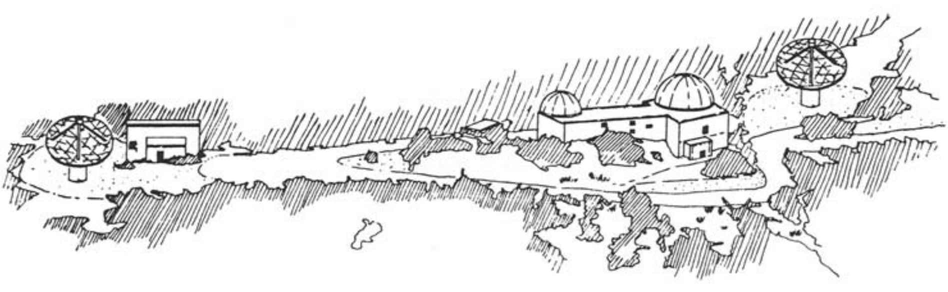

Fig. 12. Sketch of Mt. Hopkins ridge, elevation 2.3 Km, showing the present 10 m reflector and support building, two intervening optical telescopes, and the new reflector 120 m from the first reflector.

When the second reflector is equipped with its high resolution camera GRANITE should have an improved signal-to-background ratio of another order-of-magnitude compared to the present single reflector system, and an energy threshold of about 100 GeV. Thus sources with a flux of less than 10% of the Crab Nebula could be detected in a few hours. Successful operation of a 2-element array of Cherenkov imagers should pave the way for large multi-element arrays such as CASITA (Akerlof 1990[46]) which could become operational by the middle of the decade.

5.0 Conclusions

The detection of the Crab Nebula by the Whipple Observatory's 10 m telescope proves the effectiveness of the Cherenkov image technique for sensing TeV gamma rays in the presence of a large cosmic-ray background. With the addition of the GRANITE reflector for stereoscopic viewing, sources fainter than 0.1 Crab can be detected. However, it is a sobering thought that this level of sensitivity allows a compact source with the intrinsic luminosity of the Crab Nebula to be detected only if it is closer than the center of our galaxy. Even greater sensitivity is needed to probe the galaxy completely. Therefore, other techniques of background rejection need to be explored and developed to their utmost. Detection systems of the future should incorporate all promising techniques. At +22° declination the Crab Nebula can serve as a "standard candle" to judge potential hardware and software improvements for all northern observatories. (For southern observatories the Vela pulsar may serve the same purpose.)

The launch of the Gamma Ray Observatory in the spring of 1991 is eagerly awaited. In particular the EGRET[47] instrument should survey the 20 MeV - 10 GeV sky uniformly to a flux level of a few percent of that of the Crab Nebula, providing numerous targets for TeV viewing.

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