in the dark night sky. Although this system adds noise to each channel, it is considered essential if stable trigger conditions are to be maintained between the on and off regions. Because the 10 m reflector is on an altazimuth mount, the star field slowly rotates as the source is tracked sidereally. The presence of a bright star ($m_r < +3.0$) in the field of view may exceed the condenser lamp’s ability to compensate for the changing light level in a particular phototube. If so, that phototube is turned off for the duration of the on and off scans.

Typically the trigger rate in each channel was 1 Hz, and the event trigger rate was 3–4 Hz at the zenith. The latter had a zenith angle dependence that went as $R = R_0 \cos^{-2.5} z$, where $R_0$ is the rate at the zenith and $z$ is the zenith angle. The random rate from night-sky fluctuations was negligible, but there was a small zenith-angle dependent contribution to the trigger rate from cosmic-ray particles physically passing through two or more adjacent phototubes in a single box.

The rate was measured to be 0.01–0.03 Hz.

The accuracy of which the sky image character can be made up of two types of noise present in the record sky heights: (1) shot noise in the signal itself; (2) noise due to fluctuations in the night-sky-light plus paddling lamp, which is also a form of shot noise; (3) pickup, electronic noise, etc., downstream of the phototubes. The latter was found to be negligible under operating conditions (dark night sky).

Under operating conditions (dark night sky), the average current in each phototube is 0.33 photoelectron per sec. The night-sky noise is effectively the fluctuation in this number within the 45 nsec integration time of the camera. Artificial triggers of the camera permitted this number to be measured; the result is $\sim 5.9$ photoelectrons per channel per gate width. The minimum possible is 3.9 photoelectrons, which is the Poisson standard deviation in the number of photoelectrons emitted by the photocathode. Thus we find a value 1.5 times the Poisson value.

Shot noise in the signal itself was measured by consideration of the fluctuations when the camera is triggered by a pulsed nitrogen discharge tube which uniformly illuminates each phototube (Lewis et al. 1987). These nitrogen flash images indicated that the measured signals show fluctuations that are 1.3 times the expected Poisson deviation, in approximate agreement with value derived above. These results are consistent with the expected noise due to the statistics of the dynode secondary emission process.

Absolute calibration of the camera is based upon consideration of the above noise levels and from a direct measurement using a calibrated radioactive light source on the face of each phototube. The light source was calibrated using an acrylic Cerenkov muon telescope (Gorham 1986). These measurements indicated a conversion factor of 1.4 photoelectrons per digital count. The trigger level for each of the 19 inner tubes was $\sim 50$ electrons.

c) Observations

The on/off tracking technique was generally used for the observations of the Crab Nebula. The typical procedure was to...
Fig. 1. Different form of showers generated by gamma-rays and protons. On the left, a 320 GeV gamma shower; on the right a 1 TeV proton. The lateral scale is exaggerated by a factor 5. The picture is thinned down by showing each track as a sparsely dashed line.

in points of emission of Čerenkov photons – is somewhat different in the two cases: proton showers have a longer penetrating tail, some particles reaching the ground and giving a more intense Čerenkov radiation near the shower axis. Figure 3 shows the average distribution in atmospheric depth of the emitted light, but omitting light emitted directly by muons. The muons, in proton showers, do penetrate to the ground over a wide area, and an intense local peak of Čerenkov light is seen around each muon impact point. Proton showers show much greater shower-to-shower fluctuations in longitudinal profile than do gamma showers. Figure 4 illustrates typical cases (again omitting the more widely spread muon "tail", to make the point that even the core electron-photon cascades differ for the two types of shower). These differences in longitudinal profile will not, however, identify every proton shower. Showers due to heavy nuclei of the cosmic radiation are even more well distinguished from gamma showers. For the same energy, they are even more laterally diffuse, and contain more muon tracks, contributing to patchy muon light (at TeV energies).
Fig. 2. Average lateral distributions of Čerenkov light at about 700 GeV

Fig. 3. Average longitudinal distribution of Čerenkov emission

2.1. Main characteristics of Čerenkov light from showers

Figure 5 shows schematically the anatomy of Čerenkov light in a shower.
Figure 2, below, shows the distribution of the widths, lengths, and other parameters of background proton showers, and for showers from oxygen nuclei, compared with those for gamma-ray showers (shaded histogram) from a source placed in the centre of the field of view. Units: degrees — except for FRAC(2), which is dimensionless. The triggering requirement is

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APPENDIX

Suppose the \(i\)th phototube is given coordinates \(x_i, y_i\) (in degrees) and registers a signal \(s_i\). The origin of the coordinates will be the center of the array of phototubes. The axis of an image is expressed by the equation:

\[
y = ax + b.
\]

Then defining (as usual)

\[
\langle x \rangle = \Sigma s_i x_i / \Sigma s_i, \quad \langle x^2 \rangle = \Sigma s_i x_i^2 / \Sigma s_i, \quad \langle y \rangle = \Sigma s_i y_i / \Sigma s_i, \\
\langle y^2 \rangle = \Sigma s_i y_i^2 / \Sigma s_i, \quad \langle xy \rangle = \Sigma s_i x_i y_i / \Sigma s_i,
\]

and

\[
S_x^2 = \langle x^2 \rangle - \langle x \rangle^2, \quad S_y^2 = \langle y^2 \rangle - \langle y \rangle^2, \quad S_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle.
\]

If \(d = S_x^2 - S_y^2\), then

\[
a = (d + \sqrt{d^2 + 4 S_{xy}^2})/2 S_{xy}, \quad b = \langle y \rangle - a \langle x \rangle,
\]

\[
\text{width}^2 = (S_x^2 + a^2 S_y^2 - 2 a S_{xy} \sqrt{1 + a^2}), \quad \text{length}^2 = (S_y^2 + a^2 S_x^2 + 2 a S_{xy} \sqrt{1 + a^2}),
\]

\[
\text{miss} = \text{ABS}[(b)/(\sqrt{(1 + a^2)})], \quad \text{dis} = r = \sqrt{\langle x^2 \rangle + \langle y^2 \rangle}.
\]

(NOT the shower impact parameter!)

To obtain the azimuthal width \(\text{azwidth}\), we first transform to coordinates \((p, q)\) aligned along and perpendicular to the radial direction to the centroid. Then if

\[
\sin \theta = \langle y \rangle/r \quad \text{and} \quad \cos \theta = \langle x \rangle/r,
\]

\[
q = \langle x \rangle - x \sin \theta + y (1 - \langle y \rangle) \cos \theta.
\]

Then \(\text{azwidth}^2 = \langle q^2 \rangle - \langle q \rangle^2\), the means being weighted by the signal in the phototube at coordinate \((p, q)\), as in the original calculation of \(\langle x \rangle\), etc.

REFERENCES


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TeV GAMMA RAYS FROM CRAB NEBULA

![Graph](image)

**Fig. 7.—Distribution of azwidth (on - off) in terms of standard deviations as a function of azwidth**

ment of the shower and is hence quite different from width which is a strong function of the lateral spread. That it provides independent discrimination is an important confirmation of the photonic nature of the primary radiation. *Conc* is a combination of *width* and *length* and hence is not independent. *Dis* is the weakest discriminator in the simulations. This is seen to be the case here also (Table 6). When a combination of parameters is used, e.g., when four of the six parameter cuts are satisfied (as suggested by Hillas 1985), the effect is of comparable significance with the use of *azwidth* alone. An empirical selection (four out of five), with *dis* excluded, is even more significant (+8.45 $\sigma$).

**b) Previous Observations**

In an early version of the camera (Clear et al. 1983; Cawley et al. 1985b), we made a series of observations of the Crab Nebula using basically the same technique. A total of 82_observation scans were made using the same observing technique as analysis. These observations were made prior to the detailed simulations with their prediction of distinct gamma-ray domains (Hillas 1985); however, an analysis based on an empirically defined parameter, *frac(2)* (now renamed *cune*), designed to exploit the difference between the measured angular size of Cerenkov light images and the simulated size of gamma-ray images, gave an excess of events from the direction of the Crab Nebula of 3–4 $\sigma$ (Cawley et al. 1985a). An absolute significance could not be assigned to this excess since the separation into gamma-ray and background domains was empirically derived.

After the publication of the detailed simulations, this same data base was analyzed using the predicted discrimination factors (Gibbs 1987). The results are shown in Table 7. Although the statistical significance is not high, the results were sufficiently encouraging to warrant further observations using the upgraded camera.

Since there were significant differences between this
We note that (a) the percentage of events that are rejected by the \azwidth\ discrimination threshold is greater than 98\%, in agreement with the simulations (Hillas 1985); (b) there is an excess of candidate gamma-ray events in the \on\ source data of order 15\%; (c) the effect is consistent with the difference in the "all" \on/\off\ pairs, i.e., the selection has not rejected many gamma-ray events; (d) a significant excess is only seen when gamma-ray–like events are selected, so that there can be little doubt about the nature of the primary that causes the excess; (e) the cumulative total excess has a statistical significance of 8.9 \sigma; this is a level not generally encountered in very high energy or ultra high energy gamma-ray astronomy.

The overall distribution of \azwidth\ parameters for the \on\ and \off\ scans (for \z < 30\degree) are shown in Figure 6. Also shown is the difference in detail for \azwidth\ less than 0.35; this should be compared with Figures 4 and 5. Within the statistical limitations of the simulations (which were performed only for \z = 0\degree), there is good qualitative agreement. We have also added the differences in the two \azwidth\ distributions over 500 \degree for possible anomalies; these are plotted in \azwidth\ parameters with \z < 30\degree in standard deviations as a function of \azwidth\ and \azwidth\ itself. It is apparent that the only significant differences are at small values of \azwidth.

In Figure 8a we have plotted the distribution of individual (\on – \off) effects (in standard deviations) in the 175 pairs using the \azwidth\ canonical cut. To check on the run-to-run stability of the \azwidth\ distributions we have also shown the distribution of (\on – \off) effects using a cut at \azwidth > 0.7 (chosen to pass approximately the same number of events as the canonical cut passes at the other end of the distribution; i.e., \on = 15,163, \off = 15,066, \on – \off = 97 [\pm 0.56 \sigma]). It is apparent that the distributions are within statistics apart from a net positive displacement in the canonical cut distribution. For comparison, we also show the same two distributions for 36 \on/\off\ pairs of a control data set (discussed below) in Figure 8b.

### ii) Width and Miss Correlation

Both the image shape and orientation discrimination contribute to the effect seen in \azwidth, as is apparent in Table 5, in which the effect is also broken down by observing season.

### iv) Multiple Parameter Selection

A net excess from the source direction is seen when discrimination is based on any one of the three parameters, \length, \conc, or \dis. \Length\ is a measure of the longitudinal develop-

<table>
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<th>Epoch</th>
<th>\on\sources (%)</th>
<th>\off\sources (%)</th>
<th>\all\sources (%)</th>
<th>\on/\off\Difference (%)</th>
<th>Significance</th>
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<td>1986–1988</td>
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<td>651,801</td>
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<table>
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<th>Epoch</th>
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**Fig. 8:** Distribution of "all" \on\ and \off\ \azwidth\ parameters (with \z < 30\degree) for image zones 1 and 2 combined, with the differences in the two distributions in the gamma-ray domain shown in the inset.
Typical Raw Image

(a) Typical recorded event

<table>
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<tr>
<td>24</td>
<td>23</td>
<td>23</td>
<td>15</td>
</tr>
</tbody>
</table>

(b) After Calibration

| -1.5 | 6.0 | 0.0 | 100.9 |
| 1.8  | -3.5| 15.9| 114.6 |
| -3.6 | -0.4| 16.2| 71.8  |
| -2.3 | 2.2 | 7.7 | 23.8  |
| -7.4 | -4.1| 0.5 | -5.9  |
| -1.8 | 4.5 | -2.9| 0.9   |
| 2.4  | 2.1 | 1.2 | -9.6  |

(c) After Noise Reduction

| 0.0 | 0.0 | 0.0 | 100.9 |
| 0.0 | 0.0 | 15.9| 114.6 |
| 0.0 | 0.0 | 16.2| 71.8  |
| 0.0 | 0.0 | 23.8| 0.0   |
| 0.0 | 0.0 | 0.0 | 0.0   |
| 0.0 | 0.0 | 0.0 | 0.0   |
| 0.0 | 0.0 | 0.0 | 0.0   |

(d) Parameters derived from image

<table>
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<th>Gamma-ray Domain</th>
<th>Result</th>
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<td>WIDTH</td>
<td>0.13°</td>
<td>&lt; 0.14°</td>
<td>Fail</td>
</tr>
<tr>
<td>LENGTH</td>
<td>0.13°</td>
<td>&lt; 0.30°</td>
<td>Fail</td>
</tr>
<tr>
<td>NSZ</td>
<td>0.13°</td>
<td>&lt; 0.22°</td>
<td>Fail</td>
</tr>
<tr>
<td>OONC</td>
<td>0.60</td>
<td>&gt; 0.79</td>
<td>Fail</td>
</tr>
<tr>
<td>AEWIDTH</td>
<td>0.18°</td>
<td>&lt; 0.18°</td>
<td>Pass</td>
</tr>
<tr>
<td>OLS</td>
<td>0.94°</td>
<td>&gt; 0.84°</td>
<td>Fail</td>
</tr>
</tbody>
</table>

FIG. 2.—Typical image shown at various stages in the image processing: (a) raw image; (b) after pedestal subtraction and gain normalization; (c) after subtraction of subthreshold signal channels; (d) image parameters derived from (c), using the methods outlined in the appendix, and limits of gamma-ray domain.

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DISCOVERY OF A NEW TeV GAMMA-RAY SOURCE: VER J0321+211


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ABSTRACT

We report the detection of a new TeV gamma-ray source, VER J0321+211, based on observations made with the VERITAS imaging atmospheric Cherenkov Telescope Array. These observations were motivated by the discovery of a cluster of >30 GeV photons in the first year of Fermi Large Area Telescope observations. VER J0321+211 is relatively bright at TeV energies, with a mean photon flux of (1.93 ± 0.13) × 10^{-11} cm^{-2} s^{-1} above 0.2 TeV during the period of the VERITAS observations. The source is strongly variable on a daily timescale across all wavebands, from optical to TeV, with a peak flux corresponding to ~3 times the steady Crab Nebula flux at TeV energies. Follow-up observations in the optical and X-ray bands classify the newly discovered TeV source as...