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Locating very high energy γ-ray sources with arc minute accuracy

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Abstract

The angular accuracy of γ-ray detectors is intrinsically limited by the physical processes involved in photon detection. Although a number of point-like sources were detected by the COS-B satellite, only two have been unambiguously identified by time signature with counterparts at longer wavelengths. By taking advantage of the extended longitudinal structure of VHE γ-ray showers, measurements in the TeV energy range can pinpoint source coordinates to arc minute accuracy. This has now been demonstrated with new data analysis procedures applied to observations of the Crab Nebula using Čerenkov air shower imaging techniques. With two telescopes in coincidence, the individual event circular probable error will be 0.13°. The half-cone angle of the field of view is effectively 1°.

Detecting the incident direction of energetic photons is a technically difficult problem. For quanta which cannot be focussed by coherent optical techniques, there are no elegant methods for accurately determining the source location in the sky. In the energy range from 100 KeV to 40 MeV, the two most common detection methods are scintillators shadowed by coded aperture masks and Compton scattering telescopes. Both require extensive deconvolution of the data to obtain a sky image. Above the electron pair production threshold, the obtainable accuracy improves with energy but practical limitations of size and weight limited the angular precision to the order of 25 arc minutes for satellite-borne instruments such as SAS-2 and COS-B. The consequence is that even though 12 γ-ray sources are listed in the most recent COS-B catalog (Grenier, Hermsen, & Pollock 1991), only two can be unambiguously identified by their characteristic time signatures with objects observed at longer wavelengths. This obviously poses severe problems for understanding their physical characteristics. The angular resolution of the EGRET instrument on the Gamma Ray Observatory is expected to be better, in the range of 5 to 10 arc minutes (Kanbach *et al.* 1989).

Recently, ground-based experiments have demonstrated the ability to unambiguously detect TeV γ-rays from the Crab Nebula (Weekes *et al.* 1989, Akerlof *et al.* 1989a). The Čerenkov air shower technique, using a tenuous radiator (air), detects an electromagnetic shower cascade several kilometers long and a few tens of meters wide. The characteristic narrow transverse dimensions of these showers permits rejection of the far greater

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background flux of hadronically initiated events. By selecting air showers based on the predicted characteristics of Čerenkov light images, a 20 σ detection of the Crab at γ-ray energies above 400 GeV has proven the efficacy of this technique. This method has been described extensively in previous papers (Weekes *et al.* 1989, Vacanti *et al.* 1991).

The image selection reduces the hadronic background for two independent reasons. First of all, the hadronic showers are broader in width because the typical interaction imparts a transverse momentum of the order of a pion mass to the secondary particles. The comparative transverse momentum for electromagnetic showers is set by the electron mass which is 270 times smaller. Secondly, hadronic shower directions are isotropic since the trajectory of the parent charged particle is thoroughly randomized by the intervening galactic magnetic fields. Thus, a selection based on the apparent arrival direction of the shower considerably favors γ-rays from a compact source relative to the hadronic background.

Roughly speaking, Čerenkov light images of electromagnetic showers can be characterized as elongated ellipses with the major axis representing the projection of the shower trajectory on the image plane. The location of the source must lie along this axis near the tip of the light distribution corresponding to the initial interaction of the shower cascade. With a single imaging telescope, one shower image alone cannot pinpoint the source direction but many events can be combined to restrict the common phase space to a relatively small area of the sky. The characteristic ratio of shower width to length implies that the shower direction can be measured to the precision of the order of 0.2°. By averaging over N events, the source location error can be reduced by $1/\sqrt{N}$, at least until systematic errors begin to dominate. We have carried through this type of analysis for two sets of observations of the Crab Nebula, one with the telescope pointing directly at the known sky position and the other with the telescope tracking a fixed point shifted in declination by 0.4° above the Crab. The number of events associated with the Crab signal was significantly larger than 100 for both measurements so that systematic tracking errors are more significant than the statistical errors. In each case, we find that the source location reconstructed from the shower images agrees with the tracking location to approximately 2 arc minutes. At this level, the dominant error can be attributed to the telescope angle encoders and the drive system which have 5 arc minute tolerances. This performance was predicted by Hillas several years ago on the basis of Monte Carlo simulations of air shower imaging (Hillas 1989).

Two different methods have been developed to recover the spatial origin of γ-rays from the Crab Nebula. The first technique can best be understood in terms of the schematic diagram of the Whipple 10-meter telescope high resolution camera shown in figure 1 (a detailed description of this apparatus can be found in Cawley *et al.* 1990). Three different geometric structures are depicted in overlapping layers. The 109-tube photomultiplier array of the high resolution camera is shown at the lowest level. The camera consists of an inner cluster of 91 29 mm diameter tubes surrounded by an outer ring of 18 51 mm diameter tubes.

The second overlapping structure is a Cartesian grid system covering an interval of $\pm 1.0^\circ$ in both right ascension and declination directions. Each mesh point will be treated as a possible γ-ray source direction in the sky. Finally, a hatched ellipsoid depicts the outline of a typical shower image and three associated image parameters. Note that the image WIDTH and LENGTH are independent of the source position but the so-called AZWIDTH parameter depends sensitively on this assumed location. In figure 1, the indicated AZWIDTH value corresponds to a source direction at the center of the Cartesian grid. In general, each of the 441 mesh points will be associated with a different value. The procedure is to consider every mesh point as a possible source location. For each event, the image parameters are checked for compatibility with the γ-ray selection criteria previously developed (Weekes *et al.* 1989).

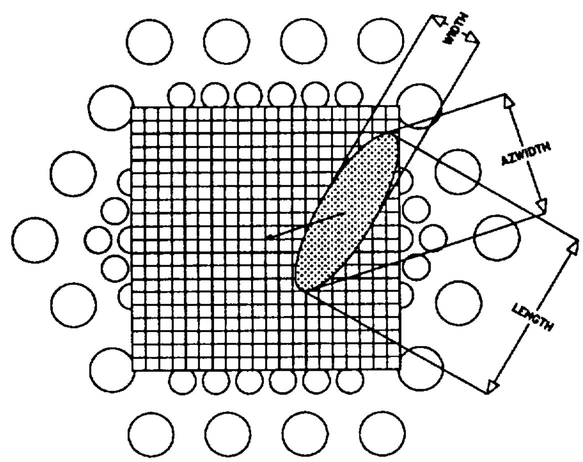

Figure 1. A schematic diagram of the analysis to evaluate the correlation of shower direction with right ascension and declination. A Cartesian grid consisting of 21 × 21 points spanning $\pm 1.0^\circ$ in right ascension and declination is shown superimposed on the 109-tube Whipple high resolution PMT camera. A typical γ-ray shower image is depicted by the shaded elliptical figure. The indicated AZWIDTH parameter is associated with the center point of the Cartesian grid.

Those mesh points far from the true source direction will tend to have large values of AZWIDTH and so few events will be consistent with γ-rays emanating from a point source from these parts of the sky. Conversely, for mesh points near the source direction, most true γ-ray events will be accepted. By carrying out this process for every shower in the data sample, a three dimensional histogram can be constructed of events versus right ascension and declination within a field of view of $\pm 1.0^\circ$. The results are shown in figure 2 for data taken on the Crab Nebula during 1988-1989. The total exposure was approximately 60 hours, divided equally between on-source and off-source observations. In figure 2a, the number of showers is plotted for data accumulated with the telescope pointed directly at the Crab Nebula and figure 2b shows data taken off-source with the telescope pointed several degrees away. Clearly, the on-source data is qualitatively different in shape. The broad central maximum apparent in the off-source data is an artifact of the event selection criteria. This effect can be reliably modeled by Monte Carlo techniques. Figure 2c shows a plot of the difference signal. The statistical significance of the signal is greater than 20 σ. As can be seen from the figure, the signal is an approximately Gaussian function of right ascension and declination with a circular probable error of 0.21° (13 arc minutes). The center of the distribution can be determined to a small fraction of this value.

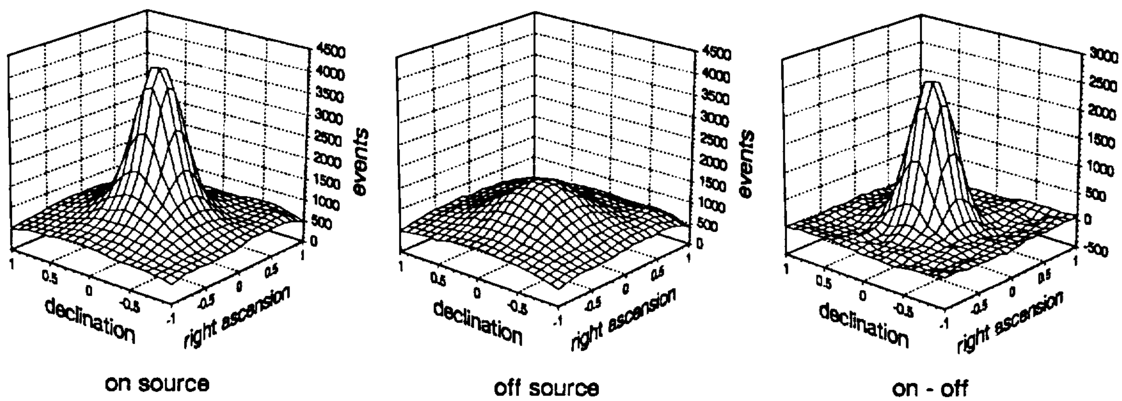

Figure 2. Histograms of data from the Crab Nebula: (a) on-source events plotted against right ascension and declination; (b) off-source events plotted against right ascension and declination; (c) on-source minus off-source events.

To prove this last point, a much shorter data exposure (4 hours on-source, 4 hours off-source) was taken with the γ-ray telescope tracking a celestial coordinate deliberately offset by a fixed angle from the Crab Nebula (0.4° in declination). The results are shown in figure 3. A contour plot of the on-source minus off-source distribution shows an 8 σ peak displaced from the origin. The center of the peak was determined by interpolation and compared with the known tracking offset. The values agreed to an accuracy of 0.036° or 2 arc minutes. The point spread function was the same as for the on-axis data discussed earlier. At this level of precision, the telescope tracking error will predominate so for future data taking, a CCD camera has been coaxially mounted to record the true sky position by simultaneous direct optical measurement of several nearby field stars. The Crab Nebula was also observed for a total of 11 hours on-source, 11 hours off-source with a 1.0° offset to the tracking

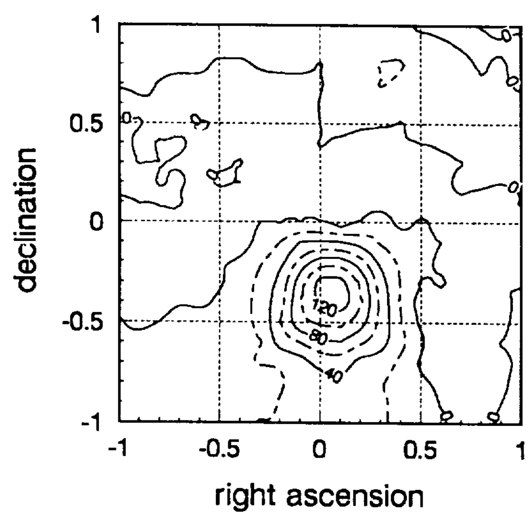

Figure 3. Contour plot of events from the 0.4° off-axis observations of the Crab Nebula plotted as a function of right ascension and declination.

direction. At this limit of the telescope field of view, the efficiency for detecting γ-rays was noticeably diminished ($\sim$ 50%). Nevertheless, a 6 σ signal was detected at the expected location.

A second analysis method has also been developed which similarly demonstrates the angular accuracy of the air shower imaging technique. The basic idea is depicted in figure 4. If the data sample is completely free of background hadronic events, the apparent source location can be obtained by finding the common intersection of the major axes of the images from two different showers. The method was applied to showers with shapes consistent with a γ-ray origin but whose orientation was completely unspecified. The analysis computed the intersection points for all possible pairs of such events, weighting each set of coordinates by the factor, sin^2(intersection angle) to compensate for the greater geometrical errors when the shower axes are almost parallel. Intersections are ignored if the distance from the intersection to the center of either shower is inconsistent with the shower's width-to-length ratio. Even with the admixture of some background, a distinctive sharp peak emerges for the Crab '88-'89 data plotted in figure 5. For a single telescope, the combinatorial background becomes relatively severe as the signal-to-noise ratio decreases. Coincident stereo shower imaging is not constrained by this problem so that figure 5 gives a good estimate of the expected performance of the Whipple twin γ-ray telescope system which is scheduled for completion in September 1991 (Akerlof *et al.* 1989b). From the on-source distribution (figure 5a), the circular probable error for a single pair of shower images was estimated to be 0.13°, (8 arc minutes). After averaging over a number of events, source coordinates should be obtainable with arc minute accuracy.

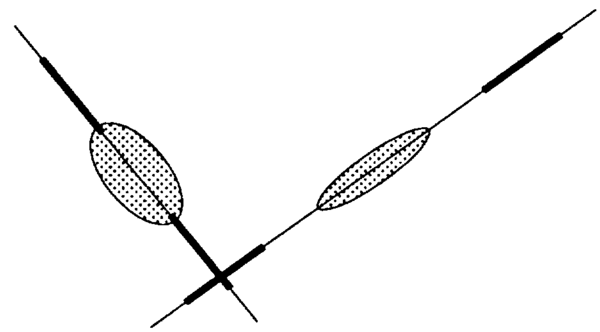

Figure 4. A schematic diagram of the shower axis intersection method for determining the γ-ray source direction. The light distribution for the two shower images is indicated by the shaded ellipses. The intersection of each possible shower pair is binned in right ascension and declination to find the most probable source location. The darkened portion of each shower axis corresponds to the expected arrival direction $\pm 0.3°$, based on the image width-to-length ratio. Only intersections of darkened lines are counted.

These analyses show that Čerenkov air shower imaging techniques are sensitive over a moderately large field of view with spatial accuracies considerably better than any other available γ-ray detector at any energy. For comparison, the COS-B collaboration quoted a circular probable error of 0.4° (24 arc minutes) for the location of Geminga. Figure 6 shows a map of radio and X-ray sources that lie within this boundary. The expected error circles for EGRET and the Whipple twin γ-ray telescope system are also plotted. The arc minute resolution of ground-based observations would almost certainly provide a unique identification of Geminga with the radio and X-ray counterparts. The single event circular probable error is still too large to distinguish if γ-ray emission from the Crab Nebula extends over the optically luminous region which covers roughly 4 by 6 arc minutes (Baade 1942) or is confined more closely to the vicinity of the pulsar.

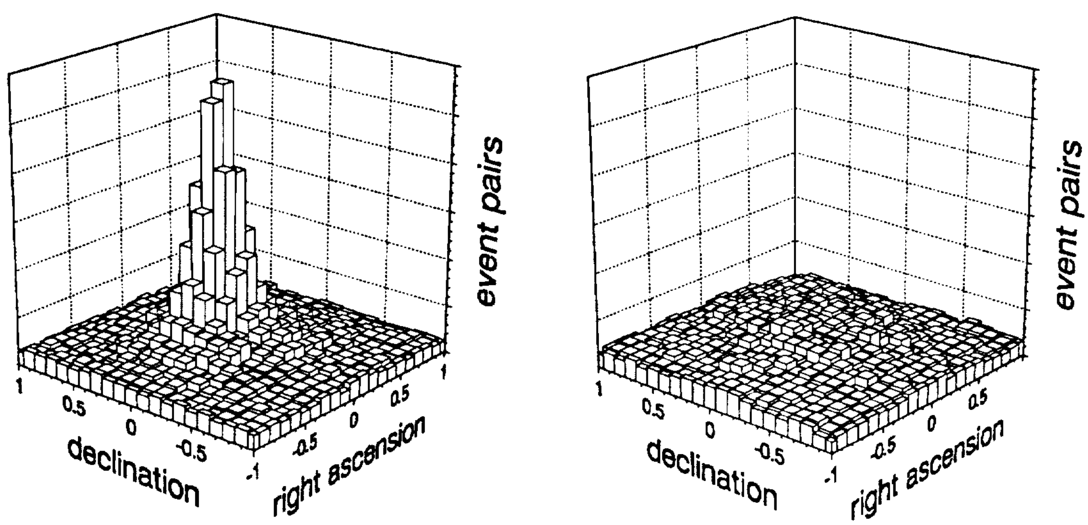

Figure 5. Histograms of shower pair intersection data from the Crab Nebula. Each event is weighted according to the prescription given in the text. (a) on-source data plotted against right ascension and declination; (b) off-source data plotted against right ascension and declination.

We can now take advantage of the image localization to double the available exposure time for data taking. In the past, equal periods were spent recording events from on-source and off-source directions. The off-source direction was typically $\pm 7.5^{\circ}$ in right ascension from the expected source coordinates. The data shown in figures 2 and 3 prove that on-source and off-source data can be recorded in overlapping fields. For example, we have recently operated in a mode where the telescope alternately tracked a sky coordinate displaced $\pm 0.5^{\circ}$ in right ascension on either side of the source of interest. The benefit is a factor of two greater exposure time with a negligible loss of apparent signal strength due to the on-off subtraction. A side benefit is an additional reduction in systematic errors since the on and off data more closely measure the same regions of sky. If the sensitivity of this new generation of VHE detectors can reach the flux levels required, ground-based experiments may provide considerable help in identifying the specific sources responsible for energetic γ-ray emission.

Acknowledgments

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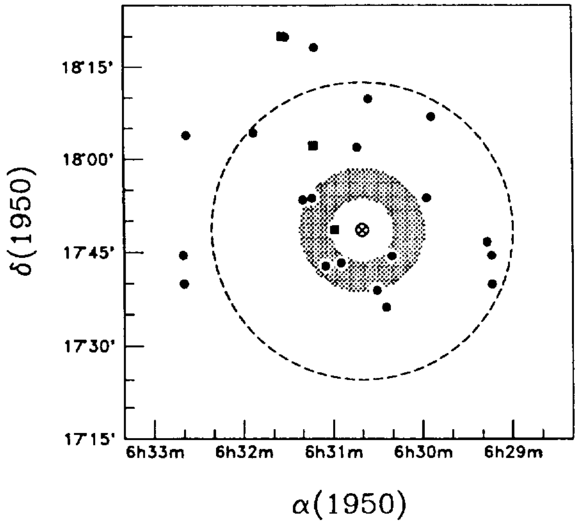

Figure 6. A plot of X-ray and radio sources near Geminga (taken from Spelstra and Hermsen 1984). The three solid squares are Einstein X-ray sources; the solid circles are radio sources measured at Westerbork. The large dotted circle shows the circular probable error for the location of Geminga. The shaded annulus is the 5-10 arc minute resolution predicted for EGRET. The inner radius of this ring corresponds to the measured resolution of the 10-meter Whipple telescope which is currently limited by the drive shaft angle encoder accuracy. The small circle near the center represents the one arc minute error obtainable with the Whipple twin Čerenkov air shower telescopes.

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