An unidentified TeV source in the vicinity of Cygnus OB2

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Abstract. Deep observation (~ 113 hrs) of the Cygnus region at TeV energies using the HEGRA stereoscopic system of air Čerenkov telescopes has serendipitously revealed a signal positionally inside the core of the OB association Cygnus OB2, at the edge of the 95% error circle of the EGRET source 3EG J2033+4118, and ~ 0.5′ north of Cyg X-3. The source centre of gravity is RA = 20h 32m 07s ±9.2′′, Dec = +41° 30′ 30″ ±2.2′′, with position uncertainty at the 3σ level. The integral flux above 1 TeV amounts ~3% that of the Crab. No counterpart of this new source is also presented.

Key words. Gamma rays: observations - Stars: early-type - Galaxy: open clusters and associations: individual: Cygnus OB2

1. Introduction

The current generation of ground-based imaging atmospheric Čerenkov telescopes offer coverage of the multi GeV to TeV γ-ray sky at centi Crab sensitivity and arc-minute resolution. Stereoscopic employed by the HEGRA CT-System at La Palma (Daum et al. 1997) offers highly accurate reconstruction of event directions at angles up to ~ 3° off-axis. Results here are taken from data originally devoted to Cyg X-3, and the EGRET source GeV J2035+4214 (Lamb & Maccabon 1997). The separation between these objects (~ 1.5′) permits a combined analysis given the overlap in their CT-System fields of view (FOV). This letter presents analysis details and observational properties of a serendipitously discovered TeV source in these data. A brief discussion concerning astrophysical origin and location of this new source is also presented.

2. Data Analysis and Results

The HEGRA system of imaging atmospheric Čerenkov telescopes (IACT-System), consists of 5 identical telescopes operating in coincidence for the stereoscopic detection of air showers induced by primary γ-rays in the atmosphere. In data dedicated to Cyg X-3, alternate ~20 minute runs targeting the Cyg X-3 position ±0.5° in declination were taken during moonless
nights of Aug-Sept 1999, Sept-Oct 2000 and Jun-Oct 2001. Likewise in data dedicated to GeV J2035+4124, ~20 minute runs were obtained tracking directly the GeV source during Jul-Aug 2001. In total, three tracking positions are present in combined data. After quality checks, a total of 112.9 hours data are available for analysis. Preferential selection of γ-ray-like events (against the cosmic-ray background) is achieved by using the difference between the reconstructed and assumed event direction, $\theta$, and the mean-scaled-width parameter, $\bar{w}$ (Konopelko 1995). In searching for weak point-like and marginally extended sources, so-called tight cuts are considered optimal given the angular resolution of the CT-System ($\prec 0.1^\circ$): $\theta < 0.12^\circ$ and $\bar{w} < 1.1$, where we use algorithm ‘3’ as described by Hofmann et al. (1999) for the event direction reconstruction. The number of images per event, $n_{\text{tel}}$, used for calculating $\theta$ and $\bar{w}$ was also $a \text{ priori}$ chosen at $n_{\text{tel}} \geq 3$. Monte Carlo simulations (Konopelko et al. 1999) and tests on real sources have shown that $n_{\text{tel}} = 2$ events contribute little to the overall sensitivity.

### 2.1. Source Search and Background Estimates

In searching for new TeV sources, skymaps of event direction excesses over the RA & Dec plane are generated after having estimated the background over the FOV. A new empirically-based template background model has been developed with the goal of simple generation of skymaps. The template background comprises events normally rejected according to the $\bar{w}$ criterion. We define the number of events in the $\gamma$-ray regime $s$ from $\bar{w} < 1.1$, and for the template background $b$ from $1.3 < \bar{w} < 1.5$. A necessary correction applied to the template background accounts for differences in radial profile between the two $\bar{w}$ regimes. A normalisation $\alpha$, to derive excess events $s - ab$ at some position in the FOV, accounts for differences in the total number of events in the two $\bar{w}$ regimes. A full description of the template model appears in Rowell (2002). Fig. 1 presents the resulting excess skymap. The template model was used in discovering the TeV source which is evident $\sim 0.5^\circ$ north of Cyg X-3. An event-by-event centre of gravity (COG) calculation (Table 2a), weighting events with $\pm 1$ from the $s$ and $ab$ regimes respectively is performed. The COG accuracy is limited by a systematic pointing error of $\sim 25^\prime$ (Pühlhofer et al. 1997). A pre-trial significance at the COG position of $+5.9\sigma$ is obtained, summing events within $\theta = 0.12^\circ$ (Table 2b). Statistical trial factors arise from the initial discovery skymap (different to that in Fig. 1) in which event directions are independently summed in 1100 bins of size $0.1^\circ \times 0.1^\circ$. Assuming 1100 trials are accrued in locating the COG, the post-trial probability $P_1 = 1.0 - (1 - P)^{1100}$ for $P$ the pre-trial probability (one-sided $P = 1.9 \times 10^{-8}$, or $+5.9\sigma$,), is then calculated as $P_1 = 2.1 \times 10^{-6}$. This gives a post-trial significance of $+4.6\sigma$. 1100 is actually a slightly conservative trial estimate since oversampling of the $\gamma$-ray point spread function (PSF) by a factor $\sim 1.5$ occurs in the discovery skymap. To verify results using the template model, we make use of a conventional type of background model employing background regions displaced from the on-source region spatially in the FOV but derived from the same $\bar{w} < 1.1$ regime. Background events are taken from ring-segments with matching trigger characteristics to that of the source region. A normalisation $\alpha$ according to the solid angle ratio between background and on-source regions is then applied. Results using this so-called ring model (Table 2b) are consistent with those from the template model.

### 2.2. Observational Properties of the TeV Source

Splitting data firstly according to their three tracking positions reveals commensurate source contributions (Table 3). The source is also found to develop linearly with the cumulative number of background events. Such tests suggest consistency with a steady source during the three years of data collection. We have also verified that after cuts a constant background acceptance throughout the dataset is observed and that the event excess in $\bar{w}$-space appears consistent with that of a true $\gamma$-ray population. To determine source size, we fit a radial Gaussian convolved with the point spread function (determined from Crab data) to the excess events as a function of $\theta^2$, using a subset of events with the best angular resolution ($n_{\text{tel}} = 5$) for which errors are minimised (Fig. 2). The intrinsic size of the TeV source is estimated at $\sigma_{\text{ src}} = 5.6^\prime \pm 1.7^\prime$. Correlations between the fit parameters suggest that the significance for a non-zero source size is at the $\sim 3.0\sigma$ level rather than the $3.5\sigma$ level indicated above. A breakdown of the excess with $n_{\text{tel}}$ also shows that the $n_{\text{tel}} = 5$ exclusive subset contributes strongly to the excess (Table 1). Such behaviour is suggestive of a generally hard spectral index given that higher trigger multiplicities are favoured by higher energy events. For
(a) Centre of Gravity
RA $\alpha_{2000}$: 20$^\circ$ 32$^\prime$ 07$^\prime\prime$ $\pm$ 9.3$^{+3.2}_{-2.2}$ sys
Dec $\delta_{2000}$: 41$^\circ$ 30$^\prime$ 30$^\prime\prime$ $\pm$ 2.0$^{+0.4}_{-0.3}$ sys

(b) Tight cuts: $\theta < 0.12^\circ$, $\bar{w} < 1.1$, $n_{\text{gal}} \geq 3$

| Background | $s$ | $b$ | $\alpha$ | $s - \alpha b$ | $S$ |
|------------|----|----|------|-------------|----|
| Template   | 523| 2327| 0.167 | 134          | 5.9 |
| Ring       | 523| 4452| 0.089 | 128          | 5.9 |

(c) Tight cuts on tracking subsets

| Back. | $t$ | $\eta$ | $s$ | $b$ | $\alpha$ | $S$ |
|-------|----|--------|----|----|------|----|
| — Cyg X-3 $\delta = -0.5^\circ$ — | — | — | — | — | — | — |
| Template | 39.5| 0.69 | 148| 647| 0.172 | +3.0 |
| Ring | 148 | 1994 | 0.057 | 3.3 |
| — Cyg X-3 $\delta+0.5^\circ$ — | — | — | — | — | — | — |
| Template | 45.4| 1.00 | 276| 1214| 0.170 | +4.2 |
| Ring | 276 | 1266| 0.168 | 3.8 |
| — GeV J2035 — | — | — | — | — | — | — |
| Template | 28.0| 0.68 | 99 | 472 | 0.156 | +2.6 |
| Ring | 99 | 1193| 0.057 | +3.4 |

$^t$: Observation time (hrs)
$^\eta$: Estimated $\gamma$-ray trigger eff. cf. on-axis.

(d) Tight cuts on $n_{\text{gal}}$ subsets

| Back. | $s$ | $b$ | $\alpha$ | $s - ab$ | $S$ |
|-------|----|----|------|---------|----|
| — $n_{\text{gal}} = 2$ — | — | — | — | — | — |
| Template | 387| 865 | 0.433 | 12 | +0.8 |
| Ring | 387 | 4619| 0.082 | 8 | +0.5 |
| — $n_{\text{gal}} = 3$ — | — | — | — | — | — |
| Template | 272| 904 | 0.224 | 70 | +4.1 |
| Ring | 272 | 2691| 0.086 | 41 | +2.6 |
| — $n_{\text{gal}} = 4$ — | — | — | — | — | — |
| Template | 133| 774 | 0.130 | 32 | +2.9 |
| Ring | 133 | 1110| 0.088 | 44 | +3.2 |
| — $n_{\text{gal}} = 5$ — | — | — | — | — | — |
| Template | 118| 777 | 0.089 | 50 | +5.1 |
| Ring | 118 | 651 | 0.102 | 52 | +5.4 |

(e) Spectral Cuts: $\theta < 0.224^\circ$, $\bar{w} < 1.1$, $n_{\text{gal}} \geq 3$

| Back. | $s$ | $b$ | $\alpha$ | $s - ab$ | $S$ |
|-------|----|----|------|---------|----|
| Ring | 366 | 3222| 0.087 | 86 | +4.7 |

1. Aharonian et al. 1999 summarise other spectral cuts.

Table 1. Summary of numerical results for the TeV source, under two background models. Here, $s$ and $b$ are the resulting event numbers for the $\gamma$-ray-like and background $\bar{w}$ regimes respectively, and $s - ab$ is the derived excess using a normalisation $\alpha$. $S$ denotes the excess significance using Eq. 17 of Li & Ma 1983. See section 2 for definitions of $\theta$ and $\bar{w}$.

Therefore to energies $> 0.8$ TeV reduces systematic errors. A so-called loose cut $\theta < 0.224^\circ$ using the ring background model is used in deriving the energy bin-by-bin excess since a loose cut in $\theta$ improves the $\gamma$-ray selection efficiency according to the moderately-extended nature of the source. Results are shown in Table 1 and Fig. 3, with the spectrum being well fit by a pure power law with generally hard photon index. Systematic errors are estimated from changes in bin centres and uncertainties in Monte Carlo-derived collection areas:

$$dN/dE = N (E/1 \text{ TeV})^{-\gamma} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$$

$$N = 4.7 (\pm 2.1_{\text{stat}} \pm 1.3_{\text{sys}}) \times 10^{-13}$$

$$\gamma = -1.9 (\pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}})$$

The integral flux at $F(E > 1 \text{ TeV}) = 4.5 (\pm 1.3_{\text{stat}}) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ amounts to 2.6% that of the Crab.

3. Discussion & Conclusion

The OB association Cygnus OB2 is unique for its compact nature and extreme number of member OB and O stars.
(eg. Knödlseder 2000), and both theoretical and observational grounds for non-thermal particle acceleration have long-been discussed (eg. Montmerle 1975, Cassé & Paul 1988, Völk & Forman 1983, White & Chen 1992). The TeV source is positioned inside the core of Cygnus OB2 as defined by Knödlseder (2000). Assuming the TeV source is as distant as Cygnus OB2 (1.7 kpc), a luminosity $\sim 10^{32}$ erg s$^{-1}$ above 1 TeV is implied, well within the kinetic energy (KE) budget of Cygnus OB2 estimated recently by Lozinskaya et al. (2002) at a few$\times 10^{39}$ erg s$^{-1}$, and also within the KE budget of a number of notable member stars (eg. Massey & Thompson 1991, Manchanda et al. 1997, Benaglia et al. 2001). So far no counterparts at other wavelengths are identified. No massive or luminous Cygnus OB2 star of note discussed recently (eg. Massey & Thompson 1991, Romero et al. 1999, Herrero et al. 2001, Benaglia et al. 2001) is positioned within the 1$\sigma$ TeV error circle. No catalogued X-ray source from the ROSAT all-sky and pointed survey lies within the 2$\sigma$ TeV error circle. Our analysis of archival ASCA GIS data yields a 99% upper limit (2–10 keV) on the flux from 3EG J2033$+4118$ presently as a MeV–PeV source (see eg. Paredes et al. 2000). In fact two nearby sources, 3EG J2033$+4118$ and also the EGRET source 1FGL J203315.1+005611 (1 Crab flux level) and flaring episodes coincident with a Cyg X-3 radio flare at energies $\geq$1 TeV is implied, further in conflict with our estimates of the flux level and steady nature of the TeV source assuming they all have the same origin. Further observations with the HEGRA CT-System aimed at confirmation and improving our spectral and source morphology studies are now underway.

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