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DETECTION OF TeV GAMMA RAYS FROM THE BL LACERTAE OBJECT 1ES 1959+650 WITH THE WHIPPLE 10 METER TELESCOPE

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ABSTRACT

We present the first strong detection of very high energy γ-rays from the close ($z = 0.048$) X-ray–selected BL Lacertae object 1ES 1959+650. Observations were made with the Whipple 10 m telescope on Mount Hopkins, Arizona, using the atmospheric Cerenkov imaging technique. The flux between 2002 May and July was highly variable, with a mean of 0.64 ± 0.03 times the steady flux from the Crab Nebula and reaching a maximum of 5 crab, with variability on timescales as short as 7 hr.

Subject headings: BL Lacertae objects: individual (1ES 1959+650) — gamma rays: observations

1. INTRODUCTION

Blazars, consisting of flat-spectrum radio quasars and BL Lacertae objects, are a relatively rare type of active galaxy characterized by extremely variable, nonthermal spectral energy distributions (SEDs). The emission extends from radio to γ-ray frequencies and is believed to be produced by a highly relativistic plasma jet closely orientated with the line of sight to the galaxy (Urry & Padovani 1995; Blandford & Rees 1978). In a νF_ν representation, the SEDs display two peaks. The lower energy peak is usually attributed to synchrotron radiation from relativistic electrons, while the higher energy peak is thought to be due to inverse Compton scattering by these same electrons. The photons involved in the scattering process may be either synchrotron photons produced in the jet, in the synchrotron self-Compton (SSC) model, or some external population, such as photons emitted from an accretion disk (Dermer, Schlickeiser, & Mastichiadis 1992) or reflected from emission-line clouds (Sikora, Begelman, & Rees 1994). Alternative explanations for the high-energy component invoke pair cascades triggered via pion and pair photoproduction from high-energy protons in the jet (Mannheim 1993, 1998) or proton synchrotron radiation (Aharonian 2000; Mücke & Protheroe 2001).

The EGRET detector on board the *Compton Gamma Ray Observatory* detected in excess of 66 blazars (Hartman et al. 1999) above 100 MeV; however, only a few have been detected at higher energies (>300 GeV) by ground-based atmospheric Cerenkov telescopes. Markarian 421 (Punch et al. 1992) and Markarian 501 (Quinn et al. 1996) were the first extragalactic TeV sources to be detected, and the behavior of these two nearby ($z = 0.031$ and $z = 0.034$, respectively) objects has been closely monitored and studied. Flux variability over 2 orders of magnitude has been observed, with doubling timescales as short as ~15 minutes (Gaidos et al. 1996), placing strong constraints on the size of the emission region. The γ-ray flux is correlated with the X-ray flux (Buckley et al. 1996; Catanese et al. 1997a; Krawczynski et al. 2000) and, in the case of Mrk 421, with the spectral power-law index in the γ-ray region (Krennrich et al. 2002; Aharonian et al. 2002a). Unconfirmed detections of 1ES 2344+514 (Catanese et al. 1998) and PKS 2155−304 (Chadwick et al. 1999) have also been reported, and, most recently, the detection of very weak emission from H1426+428 has been confirmed by three groups (Horan et al. 2002; Aharonian et al. 2002b; Djannati-Atai et al. 2002). This last object is of particular interest since it is relatively distant ($z = 0.129$) and hence the observed flux is expected to be strongly attenuated by absorption via pair production on the extragalactic infrared background light (EBL; Gould & Schrèder 1967; Stecker, De Jager, & Salamon 1992).

All of the TeV blazars can be classified as high-frequency peak BL Lac objects (HBLs; Padovani & Giommi 1995) on the basis of the location of the lower energy peak in their SEDs, and predictions of TeV emission from other nearby sources of

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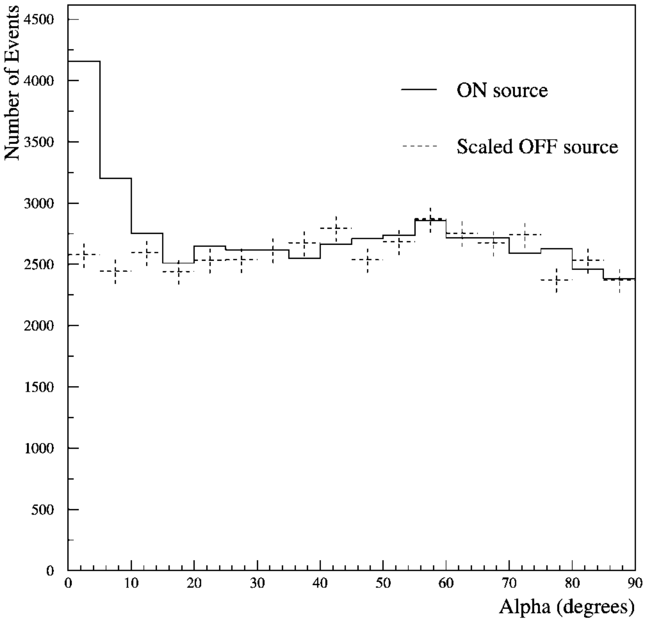

FIG. 1.—Distribution of alpha for all on- and off-source events (the off-source distribution has been scaled so as to match the number of events in the $\alpha > 30°$ region). Alpha is defined as the angle between the major axis of an elliptical γ-ray image and the source location in the camera.

this type have driven observations by atmospheric Cerenkov detectors. The source 1ES 1959+650 ($z = 0.048$) was first suggested as a good TeV candidate of this type by Stecker, De Jager, & Salamon (1996), who used simple scaling arguments to predict it as the third strongest TeV blazar, after Mrk 421 and Mrk 501, with a flux prediction of 1.9×10^{-11} cm^{-2} s^{-1} above 300 GeV. More recently, Costamante & Ghisellini (2002) have predicted fluxes above 300 GeV of 7.5×10^{-11} cm^{-2} s^{-1}, based on a simple phenomenological parameterization of the SED adapted from Fossati et al. (1998), and 0.03×10^{-11} cm^{-2} s^{-1} using a homogeneous, one-zone SSC model (Ghisellini, Celotti, & Costamante 2002).

In fact, 1ES 1959+650 is not a particularly extreme example of an HBL. Measurements with *BeppoSAX* in 1997 (Beckmann et al. 2002) placed the lower energy SED peak at 10^{15} Hz (4 eV), as compared to typically ~1 keV for Mrk 421 (Maraschi et al. 1999) and ~100 keV for Mrk 501 during its 1997 flare state (Pian et al. 1998), although for both of these sources the position of the peak is known to vary widely depending on the flux level. Giebels et al. (2002) report on X-ray observations of 1ES 1959+650 obtained with the Unconventional Stellar Aspect (1–16 keV) and the *Rossi X-Ray Timing Explorer* (*RXTE*; 2–16 keV) missions during 2000, showing threefold increases in the X-ray flux on a timescale of a few days. The flux increase is correlated with spectral hardening, indicative of a shift of the lower energy peak of the SED toward higher frequencies. The source is also unusual among HBLs for its strong rapid optical variability. Observations by Villata et al. (2000) showed rapid flickering, including a decrease of 0.28 mag in 4 days.

Prior to 2002 May, only tentative evidence had been presented for TeV emission from 1ES 1959+650. A detection with a statistical significance of 3.9 σ was reported by Nishiyama et al. (1999) based on 57 hr of observations with the Utah Seven Telescope Array. More recently, Konopelko et al. (2002) reported a preliminary detection at ~5 σ for the High-Energy Gamma-Ray Astronomy (HEGRA) Cerenkov telescope system. Previous observations of 1ES 1959+650 with the Whipple 10 m telescope produced an upper limit at a flux level of 1.3×10^{-11} cm^{-2} s^{-1} above 350 GeV (Catanese et al. 1997b).

Observations of 1ES 1959+650 during 2002 May–July with the Whipple 10 m telescope resulted in a clear detection of TeV γ-ray emission from this object (Dowdall, Moriarty, & Kosack 2002), which was rapidly confirmed by the HEGRA experiment (Horns & Konopelko 2002). We report here the results of the Whipple 10 m observations.

2. OBSERVATIONS AND DATA ANALYSIS

The configuration of the Whipple 10 m γ-ray telescope during these observations is described in detail in Finley et al. (2001). Briefly, the telescope consists of a 10 m reflector and a 490 pixel photomultiplier tube (PMT) camera. For the purposes of this analysis, only the high-resolution (0°.12 spacing) central 379 PMT pixels have been used. Cerenkov images are recorded and parameterized according to Hillas (1985), and then γ-ray–like images are selected using the "supercuts" criteria (Reynolds et al. 1993) optimized on recent data from the Crab Nebula, the standard candle of TeV γ-ray astronomy (Weekes et al. 1989). Following a realignment of the optical system in 2002 February, observations of the Crab Nebula showed that the telescope was at its most sensitive since the installation of the current camera, with 1 hr of Crab observations producing a 6 σ detection; however, between 2002 February and July a decrease in the relative efficiency of the telescope of ~30% was measured by examining the response to the cosmic-ray background. The cause of the effect is still under investigation—one explanation may be that it is due to increased atmospheric absorption caused by large forest fires in the region during this period.

Observations of 1ES 1959+650 were made during moonless periods between 2002 May 16 and July 8. The total data set consists of 39.3 hr of on-source data, together with 7.6 hr of off-source data for background comparison. For observations from Mount Hopkins (latitude N31°57′.6), 1ES 1959+650 culminates at a zenith angle (θ_z) of 33°.5, and so the data were necessarily taken at large θ_z, between 53°.5 and 33°.5. After accounting for the zenith angle and reduced telescope efficiency, we estimate the energy threshold ($E_{\rm thresh}$) for the majority of the observations to be ~600 GeV; $E_{\rm thresh}$ is defined here as the energy of the peak differential γ-ray flux for a source with the same spectrum as the Crab Nebula. Figure 1 shows the distribution of the Cerenkov image orientation angle alpha for the full on-source data set, together with the distribution for the off-source data set scaled such that the number of events in the region $\alpha > 30°$ is the same. The average rate of the excess in the on-source γ-ray region at $\alpha < 15°$ is $1.08 \pm 0.05\ \gamma$ minute^{-1}, corresponding to a detection of greater than 20 σ.

3. FLUX VARIABILITY

Figure 2 shows the daily averaged rates for 1ES 1959+650 for all of the observations. The rates are expressed in multiples of the steady Crab Nebula flux and have been corrected in order to account for the varying zenith angle and changes in telescope efficiency according to the procedure of LeBohec & Holder (2002). This has been tested using Crab Nebula data taken over a wide range of zenith angles and atmospheric conditions. The correction factor varies from run to run and has a mean value for this data set of 2.0% ± 20%. Strong night-to-night variability is evident; the largest change in rate, be-

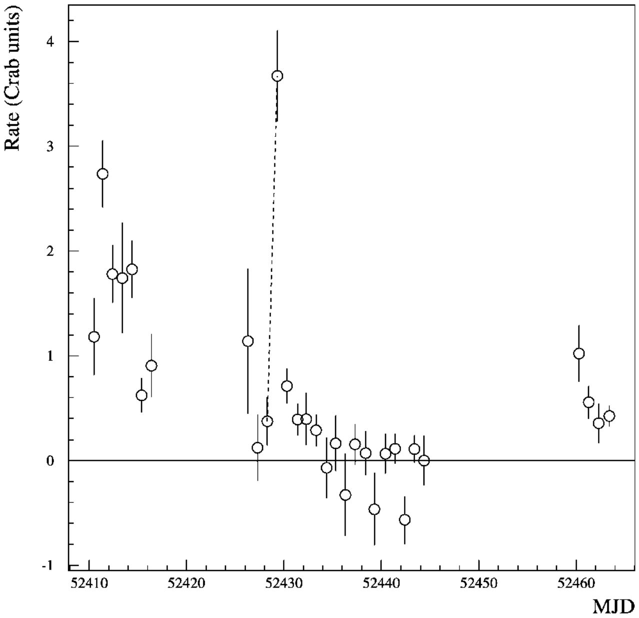

FIG. 2.—Daily average γ-ray rates for 1ES 1959+650 during 2002. The rates have been corrected for zenith angle of observation and relative telescope efficiency as described in the text. The dashed line indicates the most rapid rate change, corresponding to a doubling time of 7 hr.

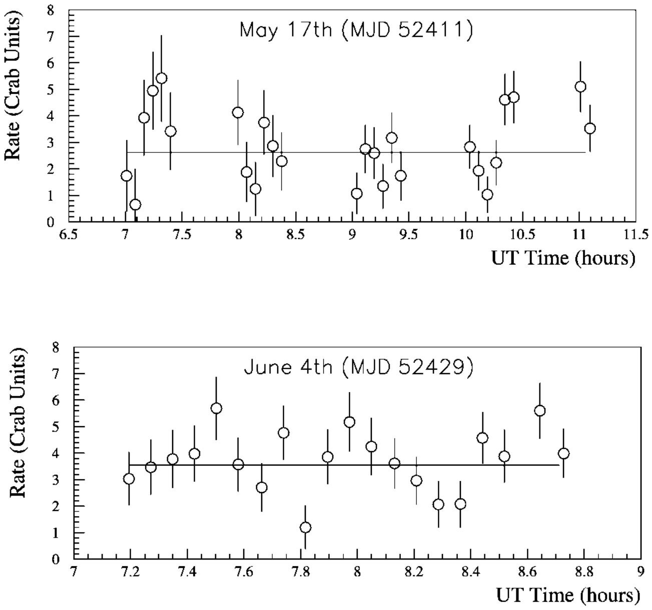

FIG. 3.—The γ-ray rates for the two nights showing the most activity (5 minute binning). The rates have been corrected for zenith angle of observation and relative telescope efficiency as described in the text.

tween MJD 52,428 and MJD 52,429, corresponds to a doubling time of 7 hr—shorter than has ever been observed in other wave bands for this source. The mean flux over all observations was 0.64 ± 0.03 crab.

Figure 3 shows the rate in 5 minute bins for two nights, May 17 and June 4, during which the source was most active. The statistical evidence for variability within these nights is given by the χ^2 probabilities of constant emission $=1\%$ and 8%, respectively. We conclude that there is no strong evidence for flux variability on this timescale.

4. DISCUSSION

The detection of TeV γ-ray emission from 1ES 1959+650 adds another member to the class of TeV blazars, all of which are close BL Lac objects having a low bolometric luminosity and the peaks in their SEDs at high frequency. The rapid flux variability, and the fact that 1ES 1959+650 has not been detected during previous observations, indicates that the source was in an unusual flaring state during these observations. The flux level was at times orders of magnitude above the most recent model predictions. Throughout the period of the Whipple observations, measurements in the 2–12 keV region by the All-Sky Monitor on board *RXTE* have shown 1ES 1959+650 to be active and variable, with daily average fluxes reaching ~20 mcrab in May and July. Target of opportunity observations with the *RXTE* small field-of-view instruments were triggered following the γ-ray detection and will be reported on elsewhere (H. Krawczynski 2002, private communication). The rapid flux variability observed at TeV energies implies a small emission region in the jet with a high Doppler factor (Mattox et al. 1993; Madejski 1996; Buckley et al. 1996). The contemporaneous X-ray and TeV γ-ray data will allow us to constrain the jet parameters when modeling the emission processes.

Analysis of the Whipple data is ongoing, but attempts to reconstruct the source spectrum have been hampered by the effects of the decreased telescope efficiency during the observation period. The HEGRA collaboration measure a rather steep spectrum (spectral index $\alpha = 3.2 \pm 0.3$) for observations prior to 2002, while the spectrum during the flaring period exhibits pronounced curvature and deviates significantly from the spectrum seen during the quiescent state (Horns et al. 2002). The majority of models for the EBL lead to predictions of a cutoff in the γ-ray region beginning below ~10 TeV for a source at $z = 0.048$ (Primack 2001; but see Vassiliev 2000 for a discussion of an EBL model that does not produce a distinct feature in the observed spectrum). Deviations from a pure power law have now been resolved in the spectra of both Mrk 421 (Krennrich et al. 2001; Piron et al. 2001; Aharonian et al. 2002a) and Mrk 501 (Samuelson et al. 1998; Aharonian et al. 1999; Djannati-Atai et al. 1999), and the spectrum of the most distant TeV blazar, H1426+428, is measured to be very steep [$\alpha = 3.50 \pm 0.35(\mathrm{stat}) \pm 0.05(\mathrm{syst})$; Petry et al. 2002], but it is not yet clear whether these features are due to absorption on the EBL or are intrinsic to the sources. Clearly, further observations and spectral analysis of 1ES 1959+650 may help to resolve this question.

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