The Astrophysical Journal, 690:L126–L129, 2009 January 10
doi:10.1088/0004-637X/690/2/L126

DISCOVERY OF VERY HIGH ENERGY GAMMA-RAY RADIATION FROM THE BL LAC 1ES 0806+524

V. Acciari[1], E. Aliu[2], T. Arlen[3], M. Bautista[4], M. Beilicke[5], W. Benbow[6], M. Böttcher[7], S. M. Bradbury[8], J. H. Buckley[5], V. Bugaev[5], Y. Butt[9], K. Byrum[10], A. Cannon[11], O. Celik[3], A. Cesarini[12], Y. C. Chow[3], L. Ciupik[13], P. Cogan[4], P. Colin[14], W. Cui[15], R. Dickherber[5], C. Duke[16], T. Ergin[9], A. Falcone[17], S. J. Fegan[3], J. P. Finley[15], G. Finnegan[14], P. Fortin[18], L. Fortson[13], A. Furniss[19], D. Gall[15], K. Gibbs[6], G. H. Gillanders[12], J. Grube[11], R. Guenette[4], G. Gyuk[13], D. Hanna[4], E. Hays[20], J. Holder[2], D. Horan[21], C. M. Hui[14], T. B. Humensky[22], A. Imran[23], P. Kaaret[24], N. Karlsson[13], M. Kertzman[25], D. Kieda[14], J. Kildea[6], A. Konopelko[26], H. Krawczynski[5], F. Krennrich[23], M. J. Lang[12], S. LeBohec[14], G. Maier[4], A. McCann[4], M. McCutcheon[4], J. Millis[27], P. Moriarty[1], R. Mukherjee[18], T. Nagai[23], R. A. Ong[3], A. N. Otte[19], D. Pandel[24], J. S. Perkins[6], D. Petry[28], M. Pohl[23], J. Quinn[11], K. Ragan[4], L. C. Reyes[29], P. T. Reynolds[30], E. Roache[6], J. Rose[8], M. Schroedter[23], G. H. Sembroski[15], A. W. Smith[10], D. Steele[13], S. P. Swordy[22], M. Theiling[6], J. A. Toner[12], L. Valcarcel[4], A. Varlotta[15], V. V. Vassiliev[3], R. G. Wagner[10], S. P. Wakely[22], J. E. Ward[11], T. C. Weekes[6], A. Weinstein[3], R. J. White[8], D. A. Williams[19], S. Wissel[22], M. Wood[3], and B. Zitzer[15]

[1] Department of Life and Physical Sciences, Galway-Mayo Institute of Technology, Dublin Road, Galway, Ireland
[2] Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
[3] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
[4] Physics Department, McGill University, Montreal, QC H3A 2T8, Canada; peter.cogan@mail.mcgill.ca
[5] Department of Physics, Washington University, St. Louis, MO 63130, USA
[6] Fred Lawrence Whipple Observatory, Harvard-Smithsonian Center for Astrophysics, Amado, AZ 85645, USA
[7] Astrophysical Institute, Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA
[8] School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
[9] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[10] Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA
[11] School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[12] School of Physics, National University of Ireland, Galway, Ireland
[13] Astronomy Department, Adler Planetarium and Astronomy Museum, Chicago, IL 60605, USA
[14] Physics Department, University of Utah, Salt Lake City, UT 84112, USA
[15] Department of Physics, Purdue University, West Lafayette, IN 47907, USA
[16] Department of Physics, Grinnell College, Grinnell, IA 50112-1690, USA
[17] Department of Astronomy and Astrophysics, 525 Davey Lab, Pennsylvania State University, University Park, PA 16802, USA
[18] Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA
[19] Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA
[20] N.A.S.A./Goddard Space-Flight Center, Code 661, Greenbelt, MD 20771, USA
[21] Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France
[22] Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA
[23] Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
[24] Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA
[25] Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA
[26] Department of Physics, Pittsburg State University, 1701 South Broadway, Pittsburg, KS 66762, USA
[27] Department of Physics, Anderson University, 1100 East 5th Street, Anderson, IN 46012, USA
[28] European Southern Observatory, Karl-Schwarzchild-Strasse 2, 85748 Garching, Germany
[29] Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
[30] Department of Applied Physics and Instumentation, Cork Institute of Technology, Bishopstown, Cork, Ireland
Received 2008 November 1; accepted 2008 November 19; published 2008 December 19

ABSTRACT

The high-frequency-peaked BL Lacertae object 1ES 0806+524, at redshift $z = 0.138$, was observed in the very high energy (VHE) gamma-ray regime by VERITAS between 2006 November and 2008 April. These data encompass the two- and three-telescope commissioning phases, as well as observations with the full four-telescope array. 1ES 0806+524 is detected with a statistical significance of 6.3 standard deviations from 245 excess events. Little or no measurable variability on monthly timescales is found. The photon spectrum for the period 2007 November to 2008 April can be characterized by a power law with photon index $3.6 \pm 1.0_{\rm stat} \pm 0.3_{\rm sys}$ between ~ 300 GeV and ~ 700 GeV. The integral flux above 300 GeV is $(2.2 \pm 0.5_{\rm stat} \pm 0.4_{\rm sys}) \times 10^{-12}\,{\rm cm}^{-2}\,{\rm s}^{-1}$ which corresponds to 1.8% of the Crab Nebula flux. Non-contemporaneous multiwavelength observations are combined with the VHE data to produce a broadband spectral energy distribution that can be reasonably described using a synchrotron–self-Compton model.

Key words: BL Lacertae objects: individual (1ES 0806+524) – gamma rays: observations – ultraviolet: galaxies – X-rays: galaxies

1. INTRODUCTION

Active galactic nuclei (AGN) are galactic cores with a luminosity that dominates the host galaxy. These central engines are believed to be powered by supermassive black holes which draw surrounding matter into an accretion disk. The unified model (Urry & Padovani 1995) of AGN implies that the observed emission from AGN is a strong function of the observation angle in relation to the relativistic jet, with the highest energy observed emission beamed along the direction of the jet.

1ES 0806+524 was identified as a BL Lacertae object (Schachter et al. 1993) using radio observations from the Green Bank 91 m telescope (Becker et al. 1991) and X-ray observations from the Einstein Slew Survey (Elvis et al. 1992). The redshift of the host galaxy is $z = 0.138$ (Bade et al. 1998). The blazar 1ES 0806+524 was suggested as a candidate very high energy (VHE) gamma-ray source based on the presence of both high-energy electrons and sufficient seed photons (Costamante & Ghisellini 2002). That work predicts an intrinsic flux in the VHE regime of $\mathcal{F}_{E>0.3\,\mathrm{TeV}} = 1.36 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

Very high energy gamma-ray observations of 1ES 0806+524 reported by the Whipple Collaboration (Horan et al. 2004; de la Calle Pérez et al. 2003) indicated flux upper limits of $\mathcal{F}_{E>0.3\,\mathrm{TeV}} < 1.4 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and $\mathcal{F}_{E>0.3\,\mathrm{TeV}} < 16.8 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ from the 1996 and 2000 observing seasons and $\mathcal{F}_{E>0.3\,\mathrm{TeV}} < 1.47 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ from the 2000 to 2002 observing seasons. Observations reported by the HEGRA Collaboration (Aharonian et al. 2004) indicated an upper limit of $\mathcal{F}_{E>1.09\,\mathrm{TeV}} < 43 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ based on one hour of observations. Observations of 1ES 0806+524 in late 2006 and early 2007 with VERITAS (Cogan et al. 2007a) yielded evidence for weak emission with a statistical significance of 2.5 standard deviations in 35 hr. The data reported in Cogan et al. (2007a) are combined with the data from the 2007/2008 observing season here.

2. OBSERVATIONS AND ANALYSIS

VERITAS (Weekes et al. 2002) is an array of four 12 m diameter imaging Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona (1268 m a.s.l., 31º40′30″N, 110º57′07″W).

Observations of 1ES 0806+524 were made between 2006 November and 2007 February during the construction phase of VERITAS and from 2007 November to 2008 April during the full four-telescope operation. All observations were taken in *wobble* mode (Fomin et al. 1994), where the target is offset from the center of the field of view by $\pm0\overset{\circ}{.}3$ or $\pm0\overset{\circ}{.}5$. After quality selection to remove data suffering from poor weather or technical problems, a total of 65 hr of observations is available. These data comprise 5 hr with a T1/T2 configuration, 25 hr with a T1/T2/T3 configuration, and 35 hr with a T1/T2/T3/T4 configuration. These data were analyzed using the standard offline VERITAS data analysis package *VEGAS* (Cogan et al. 2007b). Consistent results are obtained using independent analysis packages.

Shower images of extensive air showers in each camera are gain-corrected and cleaned (Cogan 2007c) before being parameterized using a moment analysis (Hillas 1985). Prior to stereoscopic reconstruction, a pre-selection retaining images with a size greater than 75 photoelectrons, with greater than 4 pixels surviving cleaning, and with a distance from the center of the field of view to the image centroid of less than $1\overset{\circ}{.}43$ is applied. Events where only images from the two closest-spaced telescopes survive the pre-selection are rejected. Each shower is parameterized using mean-scaled width (MSW) and mean-scaled length (MSL) (Konopelko et al. 1995). Gamma-ray selection criteria of MSW < 1.16 and MSL < 1.36 are used to reject most of the background while retaining a large portion of the signal. These selection criteria were optimized assuming a source strength of 3% of the Crab Nebula flux.

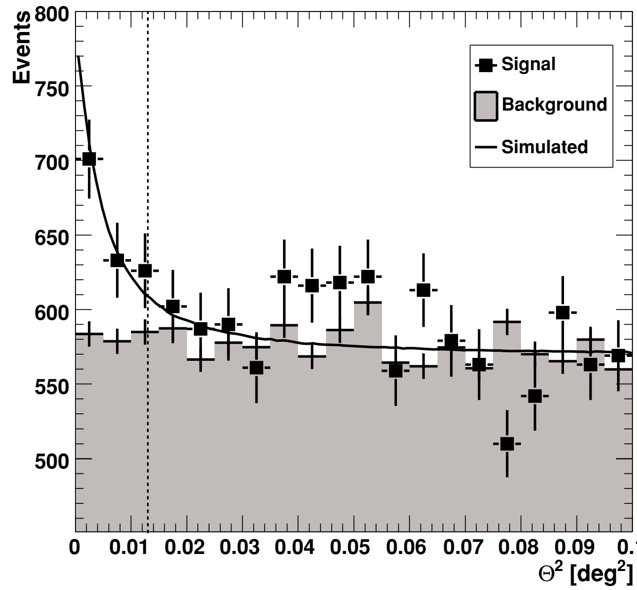

Figure 1. Distribution of the parameter θ^2, the squared angular distance between the reconstructed shower direction and the location of 1ES 0806+524. The vertical line, located at $\theta^2 = 0\overset{\circ}{.}013^2$ indicates the size of the integration region. The simulated line indicates the expected shape of the θ^2 distribution for a point source of this strength.

Background estimation is performed using the reflected-region background model (Berge et al. 2007). In this scheme, an integration region is placed around 1ES 0806+524, with background integration regions distributed around the field of view. The number of events in the integration region is termed ON, the number of events in the background region is termed OFF, and the ratio of the integration areas is termed α. As the data comprise observations with different absolute wobble offsets, a generalized version of Equation (17) from Li & Ma (1983), as noted in Aharonian et al. (2004), is used to compute the statistical significance of the excess.

The entire VERITAS dataset from 2006 through 2008 reveals the existence of VHE gamma-ray emission from 1ES 0806+524 with a statistical significance of 6.3 standard deviations above an energy threshold of $\sim$ 300 GeV. The total number of ON counts is 1543, the total number of OFF counts is 13311, and the effective ratio of the integration regions (accounting for the different wobble offsets) is $\alpha = 0.0975$, yielding an excess of 245 events.

A distribution of the squared angular distance (referred to as θ^2) between the position of 1ES 0806+524 and the reconstructed shower direction is shown in Figure 1. The integration region used in the reflected-region analysis is indicated by the vertical line situated at $\theta^2 = 0\overset{\circ}{.}013^2$. The scaled background counts are shown for comparison, and are computed using the centers of the reflected regions as the reference points. The distribution of excess gamma-ray counts is consistent with that given by a point source located at right ascension $8^{\mathrm{h}}9^{\mathrm{m}}59^{\mathrm{s}} \pm 9^{\mathrm{s}}$ and declination $52^\circ19' \pm 2'$. There is an added combined systematic angular uncertainty of $\sim 100''$. This is consistent, within error, with the position of the radio source at right ascension $8^{\mathrm{h}}9^{\mathrm{m}}49\overset{\mathrm{s}}{.}2$ and declination $52^\circ18'58''$ (Kovalev et al. 2007).

Only those data taken with four operating telescopes are used for a spectral analysis, owing to the superior energy resolution afforded. The subset of data, taken during the 2007/2008 observing period, reveals a total of 176 ON events and 1334 OFF events with a statistical significance of 4.4σ using Equation (17) from Li & Ma (1983), where $\alpha = 0.09$, yielding an excess

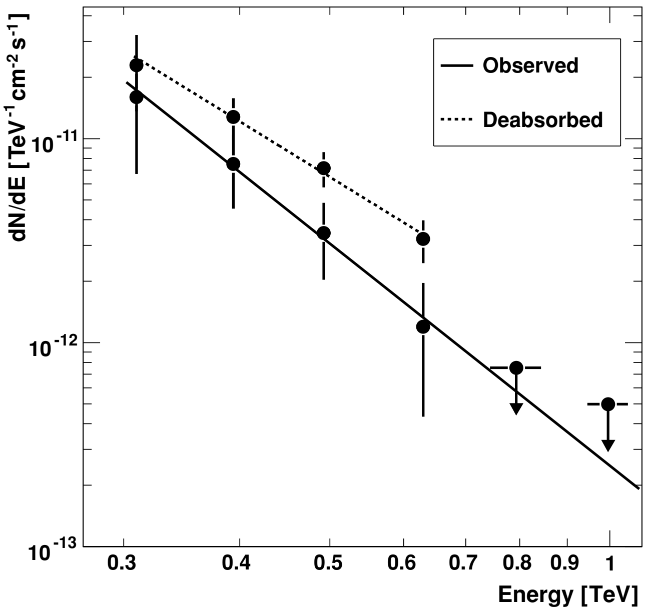

Figure 2. Differential photon spectrum of 1ES 0806+524. The spectrum is well fitted by a power law with index $3.6 \pm 1.0_{\text{stat}} \pm 0.3_{\text{stat}}$. The deabsorbed spectrum is calculated by applying the extragalactic absorption model according to Franceschini et al. (2008).

of 55 events. The differential photon spectrum can be fitted using a power law of the form $dN/dE = F_0 \times (E/400\,\text{GeV})^{-\Gamma}$ where $F_0 = (6.8 \pm 1.7_{\text{stat}} \pm 1.3_{\text{sys}}) \times 10^{-12}\,\text{cm}^{-2}\,\text{s}^{-1}$ and $\Gamma = 3.6 \pm 1.0_{\text{stat}} \pm 0.3_{\text{sys}}$ (see Figure 2). The fit yields a χ^2/dof of 0.07/2, where dof is the number of degrees of freedom. Upper limits for two spectral points above ~ 700 GeV are calculated at the 90% confidence level according to Helene (1984).

Absorption on the infrared component of the extragalactic background light results in an attenuation of high-energy photons (Gould & Schréder 1967). The absorption model according to Franceschini et al. (2008) is used to calculate the deabsorbed spectrum. This is achieved by scaling each flux point according to $\mathcal{F}_{\text{int}} = \mathcal{F}_{\text{obs}} e^{\tau(E,z)}$, where E is the energy at that flux point, z is the redshift, and τ is a function describing the absorption model. A power-law fit to the resultant flux points results in a spectral index of $-2.8 \pm 0.5_{\text{stat}}$.

The integral light curve above 300 GeV is shown in Figure 3 with the data binned per month. A constant fit yields a χ^2/dof of 6.78/5 indicating little or no measurable variability.

3. ANALYSIS OF *SWIFT* UVOT AND XRT DATA

Following the announcement of the discovery of 1ES 0806+524 by VERITAS in the VHE gamma-ray regime (Swordy 2008a), 1ES 0806+524 was observed by *Swift* (Gehrels et al. 2004) in the ultraviolet to optical and X-ray energy bands using the UVOT and XRT between 2008 March 8 and 2008 March 12. Data reduction is carried out with the HEAsoft 6.4 package. The *Swift* XRT data were taken in a photon counting mode at a rate below 0.6 counts s^{-1}, so photon pileup is not evident. The XRTPIPELINE tool is used to calibrate and clean the XRT event files. Source and background counts are extracted from circular regions of radius 30 and 40 pixels, respectively. The 0.6 to 10 keV energy spectra are fitted by a power law with fixed Galactic column density of $N_{\text{H}} = 4.4 \times 10^{20}\,\text{cm}^{-2}$ (Dickey & Lockman 1990). Marginal flux variability is seen from 2008 March 8 to 12, with the photon index hardening from $\Gamma = 2.67 \pm 0.08$ to $\Gamma = 2.53 \pm 0.07$.

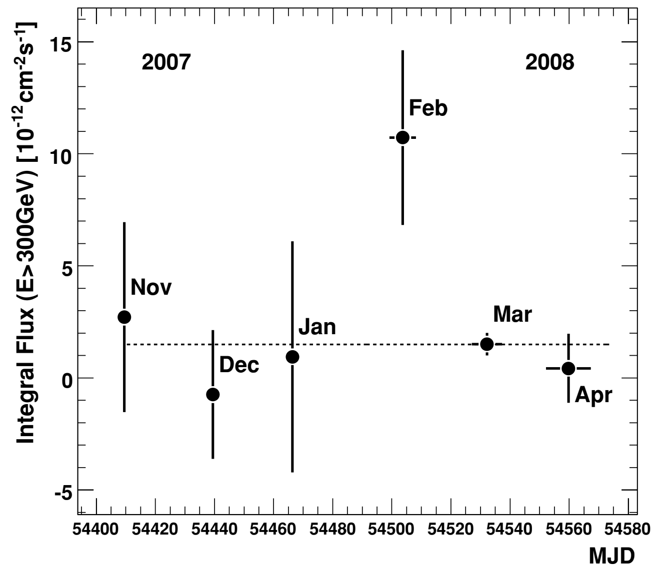

Figure 3. Month-by-month integral flux above 300 GeV from observations of 1ES 0806+524. The chi-square probability of the straight-line fit is 0.24.

Swift UVOT data are reduced with the UVOTSOURCE tool to extract counts, correct for coincidence losses, apply background subtraction, and calculate the source flux. The standard 5 arcsec radius source aperture is used, with a 20 arcsec background region. The source fluxes are dereddened using the interstellar extinction curve in Fitzpatrick (1999).

4. DISCUSSION AND MODELING

Non-contemporaneous data from the *Swift* UVOT[31] and XRT are combined with the VERITAS data and an archival optical data point (from the Tuorla 1m telescope[32]) to produce a broadband spectral energy distribution in a νF_ν representation as shown in Figure 4. The Tuorla data were taken with an R-band filter and host-galaxy subtraction is applied. The spectral energy distribution (SED) is modeled using the equilibrium version of the one-zone jet radiation transfer code of Böttcher & Chiang (2002), with parameters appropriate for a pure synchrotron–self-Compton (SSC) model. This model assumes a population of ultrarelativistic nonthermal electrons (and positrons) injected into a spherical comoving volume (referred to as the *blob*). The injection spectrum is characterized by an injection power $L_{\text{inj}}(t)$ with an unbroken power-law distribution between energies γ_1 and γ_2 with index q. The jet moves with relativistic speed βc and it is characterized by Doppler factor D which is dependent on the line of sight. The injected particles suffer radiative losses via synchrotron emission and Compton upscattering of synchrotron photons.

The SSC model has been fitted to the data, with different parameters obtained for the 2008 March 8 and 2008 March 12 data sets. For 2008 March 8, we obtain $L_{\text{inj}}(t) = 1.9 \times 10^{43}\,\text{erg s}^{-1}$ with an injection spectrum described by $\gamma_1 = 1.77 \times 10^4$, $\gamma_2 = 2 \times 10^5$, spectral index $q = 3.1$, and a magnetic field strength of 0.39 Gauss. The corresponding parameters for the 2008 March 12 data set are $1.6 \times 10^{43}\,\text{erg s}^{-1}$, $\gamma_1 = 1.6 \times 10^4$, $\gamma_2 = 2 \times 10^5$, injection spectral index $q = 2.7$, and a magnetic field strength of 0.5 Gauss. The blob radius is $5 \times 10^{15}\,\text{cm}$ in both cases. A Lorentz factor of $\Gamma = 20$ is used, with the simplifying

[31] Note that the host galaxy contribution is not important in UV.
[32] http://users.utu.fi/kani/1m/

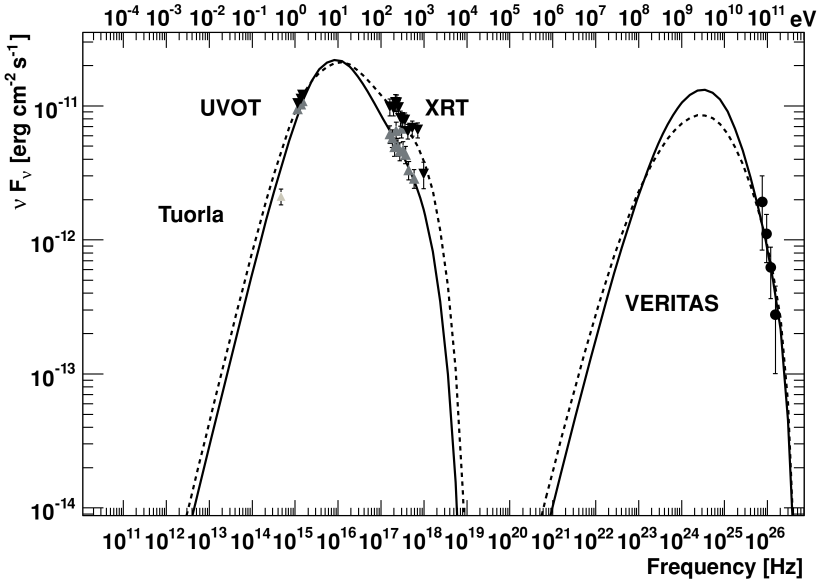

Figure 4. Broadband spectral energy distribution of 1ES 0806+524. The *Swift* data are taken on two separate nights, with a lower flux on 2008 March 8 (gray points) and a higher flux on 2008 March 12 (black points). The solid and dashed curves are SSC fits to the 2008 March 8 and 2008 March 12 *Swift* data, respectively.

assumption that the Doppler factor D is equal to the Lorentz factor. The synchrotron peak is located at $\sim 8.3 \times 10^{15}$ Hz and the inverse-Compton peak is located at $\sim 3.5 \times 10^{24}$ Hz. The system is within a factor ~ 2 of equipartition in both cases. Absorption on the extragalactic background light using the EBL scenario described by Franceschini et al. (2008) has been accounted for in the model.

5. CONCLUSIONS

VERITAS has observed the blazar 1ES 0806+524 for a total of 65 hr from 2006 November to 2008 April resulting in the discovery of VHE gamma rays with a statistical significance of 6.3σ. The differential energy spectrum between $\sim$ 300 GeV and $\sim$ 700 GeV can be fitted by a relatively soft power law with index $\Gamma = 3.6 \pm 1.0_{\text{stat}} \pm 0.3_{\text{sys}}$. The integral flux above 300 GeV is $(2.2 \pm 0.5_{\text{stat}} \pm 0.4_{\text{sys}}) \times 10^{-12}$ cm^{-2} s^{-1} which corresponds to (1.8 ± 0.5)% of the Crab Nebula flux as measured by VERITAS above 300 GeV. Assuming absorption on the infrared component of the extragalactic background light according to Franceschini et al. (2008), the intrinsic integral flux above 300 GeV is $(4.4 \pm 0.6_{\text{stat}} \pm 0.5_{\text{sys}}) \times 10^{-12}$ cm^{-2} s^{-1} which is approximately one order of magnitude less than the flux predicted by Costamante & Ghisellini (2002). The broadband spectral energy distribution can be fitted using a one-zone SSC model with standard parameters.

Observations by the EGRET gamma-ray space telescope reveal gamma-ray emission from the region around 1ES 0806+524; however the large error box indicates that the emission could be associated with either B 0803+5126 ($z = 1.14$) or 1ES 0806+524, with the former being favored (Sowards-Emmerd et al. 2003). Observations of this region with the Large Area Telescope on the *Fermi Gamma-Ray Space Telescope* should resolve the source(s) of gamma-ray emission in this region.

VERITAS is the most sensitive instrument of its kind in the Northern Hemisphere, and it is ideally suited to observations of extragalactic objects. This has been demonstrated by the detection of three new BL Lac objects by VERITAS in 2008 (Swordy 2008a, Swordy 2008b, and Acciari et al. 2008).

This research is supported by grants from the U.S. Department of Energy, the U.S. National Science Foundation, the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland and by PPARC in the UK. We acknowledge the excellent work of the technical support staff at the FLWO and the collaborating institutions in the construction and operation of VERITAS. The authors thank the anonymous referee for helpful comments which helped to improve and clarify the text.

Facilities: VERITAS, *Swift*

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