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## Recent Results from the VERITAS Collaboration

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F. Krennrich<sup>1</sup>, I.H. Bond<sup>2</sup>, S.M. Bradbury<sup>2</sup>, J.H. Buckley<sup>3</sup>, D.A. Carter-Lewis<sup>1</sup>, W. Cui<sup>4</sup>, I. de la Calle Perez<sup>2</sup>, A. Falcone<sup>4</sup>, D.J. Fegan<sup>5</sup>, S.J. Fegan<sup>6,15</sup>, J.P. Finley<sup>4</sup>, J.A. Gaidos<sup>4</sup>, K. Gibbs<sup>6</sup>, G.H. Gillanders<sup>7</sup>, T.A. Hall<sup>1,13</sup>, A.M. Hillas<sup>2</sup>, J. Holder<sup>2</sup>, D. Horan<sup>6</sup>, M. Jordan<sup>3</sup>, M. Kertzman<sup>8</sup>, D. Kieda<sup>9</sup>, J. Kildea<sup>5</sup>, J. Knapp<sup>2</sup>, K. Kosack<sup>3</sup>, M.J. Lang<sup>7</sup>, S. LeBohec<sup>1</sup>, P. Moriarty<sup>10</sup>, D. Müller<sup>11</sup>, R.A. Ong<sup>12</sup>, R. Pallassini<sup>2</sup>, D. Petry<sup>1</sup>, J. Quinn<sup>5</sup>, P.T. Reynolds<sup>14</sup>, H.J. Rose<sup>2</sup>, G.H. Sembroski<sup>4</sup>, S.P. Swordy<sup>11</sup>, V.V. Vassiliev<sup>9</sup>, S.P. Wakely<sup>11</sup>, T.C. Weekes<sup>6</sup>

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<sup>1</sup>Physics & Astronomy Department, Iowa State University, Ames, IA 50011, USA

<sup>2</sup>Department of Physics, University of Leeds, Leeds, LS2 9JT, Yorkshire, UK

<sup>3</sup>Department of Physics, Washington University, St. Louis, MO 63130

<sup>4</sup>Department of Physics, Purdue University, West Lafayette, IN 47907

<sup>5</sup>Physics Department, National University of Ireland, Belfield, Dublin 4, Ireland

<sup>6</sup>F. Lawrence Whipple Observatory, Harvard-Smithsonian CfA, Amado, AZ 85645

<sup>7</sup>Physics Department, National University of Ireland, Galway, Ireland

<sup>8</sup>Physics Department, De Pauw University, Greencastle, IN, 46135

<sup>9</sup>High Energy Astrophysics Inst., University of Utah, Salt Lake City, UT 84112

<sup>10</sup>School of Science, Galway-Mayo Institute of Technology, Galway, Ireland

<sup>11</sup>Enrico Fermi Institute, University of Chicago, Chicago, IL 60637

<sup>12</sup>Department of Physics, University of California, Los Angeles, CA 90095

<sup>13</sup>Department of Physics, University of Arkansas at Little Rock, AR 72204

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### Abstract

A decade after the discovery of TeV  $\gamma$ -rays from the blazar Mrk 421 (Punch et al. 1992), the list of TeV blazars has increased to five BL Lac objects: Mrk 421 (Punch et al. 1992; Petry et al. 1996; Piron et al. 2001), Mrk 501 (Quinn et al. 1996; Aharonian et al. 1999; Djannati-Atai et al. 1999), 1ES2344+514 (Catanese et al. 1998), H1426+428 (Horan et al. 2000, 2002; Aharonian et al. 2002; Djannati-Atai et al. 2002) and 1ES1959+650 (Nishiyama et al. 1999; Konopelko et al. 2002; Holder et al. 2002). In this paper we report results from recent observations of Mrk 421, H1426+428 and 1ES1959+650 using the Whipple Observatory 10 m telescope.

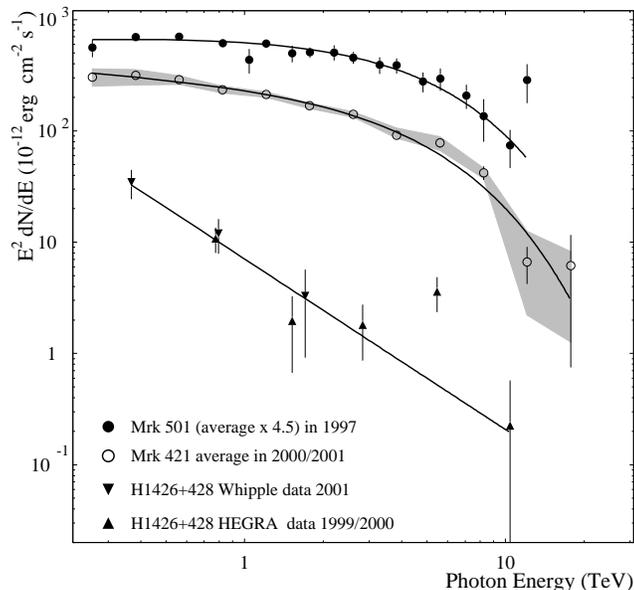
## 1. Introduction

The scientific interest in TeV blazars is manifold and ranges from classification studies of the AGN (active galactic nucleus) phenomenon and detailed studies of Doppler-boosted relativistic jets, to particle acceleration and  $\gamma$ -ray emission models near the central massive object. In addition,  $\gamma$ -ray beams traversing intergalactic space can be used to constrain and measure the diffuse extragalactic background light (EBL) through  $\gamma\gamma \rightarrow e^+e^-$  absorption. In this paper we present recent results relevant to those topics.

## 2. Broad Studies: Mrk 501, Mrk 421, 1ES2344+514, H1426+428 & 1ES1959+650

Various search strategies have been explored to build a catalogue of TeV blazars. The discovery of Mrk 421 as a TeV blazar resulted from a survey of the first EGRET catalogue of blazars (Fichtel et al. 1994), however, none of the other EGRET blazars have been detected. The focus shifted then to nearby BL Lac objects which led to the discovery of Mrk 501 as a  $\gamma$ -ray source (not in first EGRET catalogue), indicating that TeV blazars require search strategies independent from GeV sources. A striking feature in the multiwavelength spectrum of Mrk 501 is the synchrotron peak at an energy above 100 keV (Catanese et al. 1997; Pian et al. 1998) and a second peak at several hundred GeV (Samuelson et al. 1998). This provided the impetus for a refined search strategy (Catanese & Weekes 1999) selecting BL Lacs that are X-ray bright with spectra extending to hard X-rays. A systematic study that is based on a selection of X-ray and radio bright BL Lacs from X-ray and radio catalogues (Costamante & Ghisellini 2002) yielded a number of good candidates for TeV emitting BL Lacs, with H1426+428 and 1ES1959+650 among them. In fact H1426+428 was recently detected by several groups (Horan et al. 2002; Aharonian et al. 2002; Djannati-Atai et al. 2002) establishing the most distant TeV blazar that has been confirmed by several groups, with a redshift of  $z=0.129$ .

Another recent detection from the list of X-ray selected TeV candidate BL Lacs (Costamante & Ghisellini 2002) is 1ES1959+650. Observations between May 16th and July 8th 2002 yielded a strong detection (Dowdall et al. 2002; Holder et al. 2002) showing  $\gamma$ -ray flux states between 0.5 and 5 times the Crab Nebula flux. Due to its slightly larger redshift ( $z=0.048$ ) in comparison to Mrk 421 and Mrk 501 but smaller redshift than that of H1426+428, spectral studies of 1ES1959+650 will provide important additional information about the EBL (see also Holder et al. in these proceedings). In summary, the catalogue of TeV blazars is steadily



**Fig. 1.** The average energy spectrum of Mrk 501 (filled circles) in 1997 (Samuelson et al. 1998) is shown in comparison to the average spectrum of Mrk 421 (empty circles) in 2000/2001 (Krennrich et al. 2001). Furthermore, the combined energy spectrum of H1426+428 using data from the HEGRA collaboration (Aharonian et al. 2002) is shown by the upward triangles, and data from the Whipple collaboration (Petry et al. 2002) is shown by the downward pointing triangles.

increasing, indicating that they are becoming an important class of extragalactic objects for high energy astrophysics at TeV energies.

### 3. Spectral cutoffs and variability: EBL

Spectroscopic information from  $\gamma$ -ray blazars is the key to extracting the physics related to acceleration and emission processes in the relativistic jet. In addition, spectra may exhibit imprints from absorption effects of  $\gamma$ -rays due to radiation fields in the vicinity of the AGN, or attenuation of the  $\gamma$ -ray beam by the EBL. Of particular interest has been the search for signatures of  $\gamma$ -ray absorption by the EBL in the energy spectra of Mrk 501 and Mrk 421, since high flaring states in 1997 and 2001, respectively, provided excellent statistics.

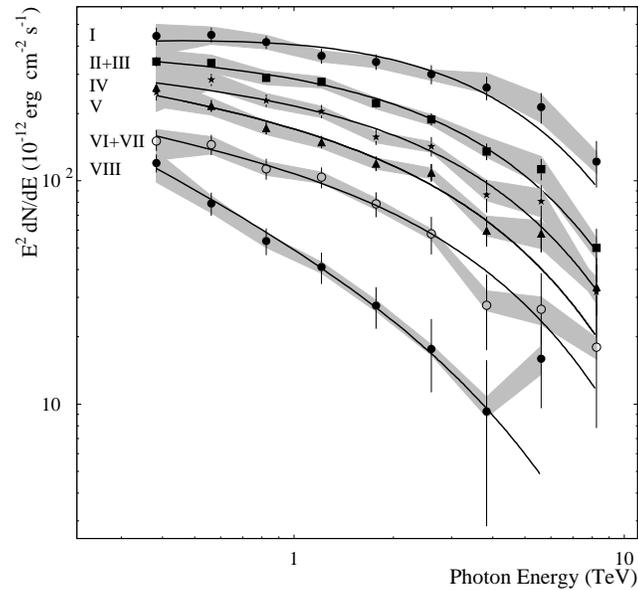
Figure 1 shows the average energy spectra of Mrk 501 and Mrk 421 for these high flaring states with flux levels reaching several Crab. Mrk 421 and Mrk 501 have similar redshifts and exhibit a cutoff in their energy spectra at  $4.3 \pm 0.3_{\text{stat}}$  TeV and  $4.6 \pm 0.8_{\text{stat}}$  TeV, respectively. The consistent cutoff energy

of approximately 4 TeV for both sources might suggest, that it is of common origin. The similarity of their distance to Earth makes absorption due to the EBL a viable possibility. The cutoffs could also be caused by a falling Klein-Nishina cross-section in an inverse-Compton picture. Other possibilities include absorption by radiation fields near the  $\gamma$ -ray source or a terminating particle energy distribution in the jet. However, since the historical synchrotron peak energies observed for both sources differ by almost two orders of magnitude, the latter scenario seems less likely.

To decide whether or not the observed cutoff is indeed due to the EBL, measurements of TeV spectra for sources at different redshifts are necessary. Although those studies are in their infancy, the energy spectrum of one of the recently detected sources with a larger redshift provides some important clues. Also shown in Figure 1 is the energy spectrum of H1426+428 between 400 GeV and 10 TeV, which can be well described by a power law with a differential flux following  $dN/dE \propto E^{-3.55 \pm 0.27}$  (Petry et al. 2002). This makes H1426+428 the TeV blazar with the softest spectrum above 400 GeV, despite the fact that H1426+428 seems to reach at times a synchrotron peak energy up to  $E > 100$  keV (Costamante et al. 2001). H1426+428 is the most distant BL Lac seen at TeV energies and theoretical studies of the EBL (Stecker & Salamon 1992; Primack 2002) suggest that its TeV  $\gamma$ -ray spectrum may be substantially attenuated through pair production off the EBL. Although the steep energy spectrum of H1426+428 concurs well with this picture, studies that could reveal the detailed shape of an attenuated spectrum require better statistics. The data published so far are consistent with a power law. Nevertheless, future measurements with better statistics should be useful for constraining the EBL density.

A promising tool in the quest for understanding the origin of spectral cutoff features is the study of spectral variability. Flaring activity of Mrk 421 in 2001 yielded  $\approx 23,000$   $\gamma$ -rays at energies  $E > 300$  GeV providing the statistics needed to carry out studies of spectral variability over an order of magnitude of flux levels (set I - set VIII). Figure 2 shows energy spectra for the 2000/2001 data of Mrk 421 binned into different flux levels. Spectral hardening with increasing flux levels is apparent from the data. Figure 3 shows the spectral index plotted versus flux (units of Crab), providing the first unequivocal evidence that TeV  $\gamma$ -ray spectra do indeed vary, placing an important observational constraint on models of particle acceleration and  $\gamma$ -ray emission in jets of AGNs. Studies of the variability of the cutoff energy should also provide important clues about the cause of the cutoff (for further discussion see Krennrich et al. 2002).

In summary, we have extended the catalogue of TeV blazars to 5 BL Lac objects. The study of their energy spectra demonstrate that spectroscopy of TeV

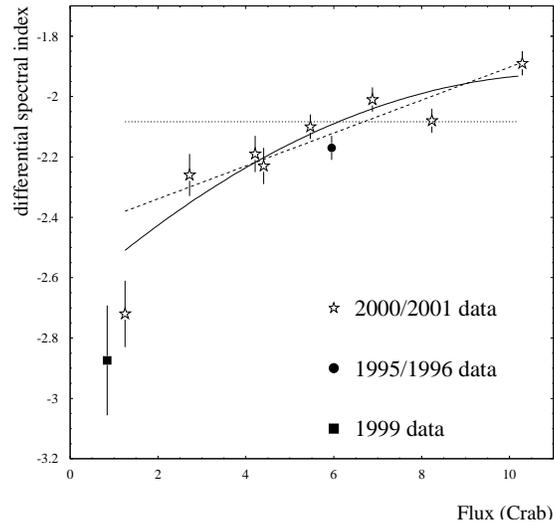


**Fig. 2.** The energy spectra of Mrk 421 averaged over 5 months are shown for different flux levels ranging from 1.3 - 10.5 Crab (Krennrich et al. 2002).

blazars is becoming a promising means to constrain the emission mechanism in their jets. In addition, an indirect measurement of the EBL between 0.1 and  $30\mu\text{m}$  is coming into reach, which will most likely be achieved by the next generation ground-based  $\gamma$ -ray telescopes CANGAROO, HESS, MAGIC and VERITAS.

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**Fig. 3.** The stars show the spectral index of Mrk 421 as a function of the flux (in units of Crab) for the 2000/2001 data, the circle shows a data point for Whipple 1995/96 data (Krennrich et al. 1999) and the square represents data taken during 1999 May-June.

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## 5. Recent Results from the VERITAS Collaboration