Observations of Active Galactic Nuclei with Ground-Based Cherenkov Telescopes

Henric Krawczynski

Washington University in St. Louis, Physics Department, 1 Brookings Drive, CB 1105, St. Louis, MO 63130

Abstract. Imaging Atmospheric Cherenkov Telescopes (IACTs) allow us to observe Active Galactic Nuclei (AGNs) in the 100 GeV to 20 TeV energy range with high sensitivity. The TeV $\gamma$-ray observations of the ten blazars detected so far in this energy range reveal rapid flux and spectral variability on time scales of several hours, sometimes even on time scales of a few minutes. While simple synchrotron-Compton models can explain the observed non-thermal emission, alternative models which involve high-energy protons are not yet ruled out. After reviewing the status of the major IACT experiments, we describe some recent observational results and their astrophysical implications. We conclude with a discussion of possible avenues for future research.

1. Introduction

The EGRET (Energetic Gamma Ray Experiment Telescope) detector on board of the Compton Gamma-Ray Observatory discovered strong MeV $\gamma$-ray emission from 66 Active Galactic Nuclei (AGNs), mainly from Flat Spectrum Radio Quasars and Flat Spectrum Radio Sources (Hartmann et al. 1999). As of this writing (August 2005), ground-based Cherenkov telescopes discovered TeV $\gamma$-ray emission from eleven Active Galactic Nuclei, only two of which were listed in the third EGRET source catalog (see Table 1 below). Ten of the eleven sources are blazars (nine BL Lac objects and the quasar H 2356-309) and combine a relatively low luminosity with Spectral Energy Distributions (SEDs) that peak at extremely high energies. The eleventh source is associated with the FR I radio galaxy M 87. The GeV/TeV emission from M 87 may originate in a qualitatively different way than in the blazar type objects, and we limit the discussion to the latter source class.

The TeV $\gamma$-ray emission from blazars is believed to originate from highly relativistic plasma outflows (jets) emanating from mass accreting black holes with the jets pointing at us. The rapid large amplitude flux variability on time scales of several minutes (Gaidos et al. 1996) suggests that the emission originates from small regions with diameters on the order of $10^{15}$ cm, less than one parsec away from the central engine. The $\gamma$-ray observations allow us to probe the structure of AGN jets very close to the central engines and thus to gain key insights into the processes of accretion onto a supermassive black hole and jet formation. While we focus here on blazars with TeV emission (see also Krawczynski 2004; Tavecchio 2004), reviews on observations and models of sources with MeV/GeV emission can be found in Sikora et al. 2001; Coppi 1999). Broader overviews of the field of TeV $\gamma$-ray astronomy are given in Buckley 2001; Ong 2003; Weekes 2003; Aharonian 2004.
2. Status of the Major Imaging Atmospheric Cherenkov Telescope Experiments

The technique of detecting $\gamma$-rays with Imaging Atmospheric Cherenkov Telescopes (IACTs) was pioneered by the Whipple collaboration with the 10 m Whipple telescope. Using a fast pixilated camera, the collaboration succeeded in discovering the first galactic TeV $\gamma$-ray source, the Crab Nebula between 1986 and 1988 (Weekes et al. 1989), and the first extragalactic TeV $\gamma$-ray source, the BL Lac object Mrk 421, in 1992 (Punch et al. 1992). While the Whipple collaboration pioneered the use of an imaging camera, the HEGRA (High Energy Gamma-Ray Astronomy) collaboration showed that an array of telescopes operated as a single detector can suppress the dominant Cosmic Ray and muon induced backgrounds very effectively and can achieve a very high sensitivity (Daum et al. 1997).

The successor experiment of the Whipple 10 m is the Very Energetic Radiation Imaging Telescope Array System (VERITAS) consisting of four (eventually seven) 12 m diameter Cherenkov telescopes (Weekes et al. 2002). The first VERITAS telescope has been taking data since April 2004 (Fig. 1) and the second will be operational in October 2005 (Holder et al. 2005). While the first two telescopes have temporarily been assembled at Mount Hopkins (AZ), the third and fourth telescopes will be built at Kitt Peak (AZ), and the first two telescopes will be moved to the latter site to form the full four-telescope array in mid 2006.

The High Energy Stereoscopic Array (H.E.S.S.) (Hinton et al. 2004) and Major Atmospheric Gamma Imaging Cherenkov detector (MAGIC) (Bastieri et al. 2004) succeeded the HEGRA and CAT (Cherenkov Array at Themis) (Barrau et al. 1998) experiments. H.E.S.S. is an array of four 12 m diameter Cherenkov telescopes located in the Khomas Highland in Namibia. The entire telescope array has been fully operational since December 2003 and has already produced spectacular science results, e.g., the detection of a sample of galactic sources in the direction of the Milky Way disk (Aharonian et al. 2005b). MAGIC presently consists of a single telescope of 17 m diameter located on the Canary Island La Palma (Spain). A second 17 m telescope is under construction. CANGAROO III consists of four telescopes of the 10 m class located in Woomera, Australia (Kawachi et al. 2001).
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| Source     | z    | Reference                  | EGRET Detection |
|------------|------|----------------------------|-----------------|
| M 87       | 0.004| Aharonian et al. 2003a     | no              |
| Mrk 421    | 0.031| Punch et al. 1992          | yes             |
| Mrk 501    | 0.034| Quinn et al. 1996          | no              |
| 1ES 2344+514 | 0.044| Catanese et al. 1998      | no              |
| 1ES 1959+650 | 0.047| Nishiyama et al. 1999    | no              |
| PKS 2005-489 | 0.071| Aharonian et al. 2005a    | no              |
| PKS 2155-304 | 0.116| Chadwick et al. 1999      | yes             |
| H 1426+428 | 0.129| Horan et al. 2002         | no              |
| H 2356-309 | 0.165| Pita et al. 2005          | no              |
| 1ES 1218+304 | 0.182| Meyer et al. 2005        | no              |
| 1ES 1101-232 | 0.186| Tluczykont et al. 2005   | no              |

Table 1. Highly significant detections of Active Galactic Nuclei by ground based GeV/TeV γ-ray telescopes (as of August 2005).

The H.E.S.S. experiment has demonstrated that the new generation of Cherenkov telescopes can achieve sensitivities on the order of 0.5% Crab for 50 hr integration times together with single photon angular and energy resolutions of 0.1° and 15%, respectively.

3. TeV Gamma-Ray Observations of Blazars

Since the discovery of TeV γ-ray emission from the BL Lac object Mrk 421 in 1992, TeV emission from other blazars has been searched for intensively. The result of this search has been the detection of TeV emission from the ten blazars listed in Table 1. The redshifts of the detected sources range from 0.031 for Mrk 421 to 0.186 for 1ES 1101-232.

The TeV γ-ray fluxes are highly variable and are frequently too low to warrant the detection on time scales of a few days. The strongest flares have been observed from the sources Mrk 421 and Mrk 501 with flux levels of about 10 times the flux from the Crab Nebula (e.g. Gaidos et al. 1996). The three sources Mrk 421, Mrk 501, and 1ES 1959+650 have shown strong flaring activity for epochs between several weeks and several months. Interpreting the flaring activity as a noise process, these long flaring phases show that this noise process has considerable power at low frequencies, and is thus similar to the “red” noise processes in X-ray binaries (Uttley et al. 2005).

Energy spectra have been measured for all blazars except for 1ES 1218+304. Fitting simple power law models \( dN/dE \propto E^{-\Gamma} \), photon indices between \( \Gamma = 2 \) and \( \Gamma = 4 \) have been reported. Significant variability of the TeV γ-ray energy spectrum has been detected for the sources Mrk 421 (Krennrich et al. 2002a, Aharonian et al. 2002) and Mrk 501 (Djannati-Atai et al. 1999). For Mrk 421, spectral variability with \( \Delta\Gamma \sim 1 \) has been found within a few hours (Krennrich et al. 2002a, Aharonian et al. 2002). The TeV flux and spectral hardness seem to be correlated in the sense that higher fluxes are accompanied by harder energy spectra. The energy spectra of Mrk 421 and Mrk 501 can be described by power law models with exponential cut-offs \( dN/dE \propto \)
While cut-off energies $E_0$ between 2.5 and 6 TeV have been reported, power law models with different \( \Gamma \)-values but with the same value of $E_0$ can fit the data from both sources (see [Krennrich et al. 2001] and references therein). Combining the data from several experiments, the H 1426+428 spectrum exhibits a pronounced kink at $\sim$1 TeV that is commonly attributed to the effect of extragalactic absorption ([Aharonian et al. 2003b]).

The acquisition of good multiwavelength data sets has encountered substantial difficulties as the TeV observatories require flares for sampling the TeV light curves on a time scale of hours. Some sources were observed with excellent multiwavelength coverage but during relatively unspectacular quiescent phases; in other cases, the sources were flaring, but the fluxes were only poorly sampled in frequency space and in time. The most remarkable result from the multiwavelength campaigns is that there is good evidence for a correlation between the X-ray fluxes and the TeV $\gamma$-ray fluxes for the two sources Mrk 421 ([Buckley et al. 1996; Takahashi et al. 1996; Takahashi et al. 2000; Blazejowski et al. 2005] (see also Fig. 2) and Mrk 501 ([Djannati-Atai et al. 1999; Sambruna et al. 2000; Krawczynski et al. 2002]). The correlation shows considerable scatter (see Fig. 3) and for the source 1ES 1959+650 evidence for a TeV flare without an X-ray counterpart has been found ([Krawczynski et al. 2004]).

The spectral evolution of sources during individual flares might be a powerful tool to access the elemental processes of Fermi particle acceleration, radiative and adiabatic cooling, and diffusive escape from the emission region ([Kirk & Mastichiadis 1999]). X-ray and recently also TeV $\gamma$-ray data do show the predicted signatures: during flares the sources seem to go through clockwise and counter-clockwise loops in the X-ray or $\gamma$-ray hardness-intensity planes ([Takahashi et al. 1996; Sambruna et al. 2000; Falcone et al. 2004]). However, single sources show a wide range of different behaviours ([Takahashi et al. 2000]), indicating that the relative length of the characteristic time scales of particle acceleration and radiative cooling change from flare to flare. The lack of a pre-
vailing signature has cast doubts on whether the signatures of Fermi particle acceleration and radiative energy losses have really been observed.

No highly significant evidence has yet been found that the radio, infrared, optical or UV fluxes are correlated with the X-ray and/or the TeV γ-ray emission. See Buckley et al. (1996) for suggestive evidence of a correlation and Krawczynski et al. (2004) and Blazejowski et al. (2005) for observations lacking such evidence.

4. Recent Development in Interpreting the Data
The emission from the TeV emitting blazars is commonly attributed to the Synchrotron Self-Compton (SSC) process. Embedded in a highly relativistic jet, a population of non-thermal electrons (and possibly positrons) emits the radio to X-ray emission as synchrotron radiation. The same electron population emits γ-rays through Inverse Compton processes by electrons scattering lower energy seed photons. In the case of BL Lac objects, the lack of strong emission lines is commonly taken as evidence that ambient photon fields are not important, and that the synchrotron photons are the dominant seed photon population.

While simple SSC models can in principle describe most of the experimental data (see for example Inoue & Takahara 1996 and Tavecchio et al. 2001) there are some outstanding issues: (i) most models need a minimum Lorentz factor of accelerated particles on the order of $\gamma_{\text{min}} = 10^5$. There is no natural explanation for the minimum Lorentz factor. (ii) The particle energy density dominates by several orders of magnitude over the magnetic field density, making the radiation process highly inefficient [Kino et al. 2002; Krawczynski et al. 2002]. (iii) While the modeling of the X-ray/TeV γ-ray spectral energy distributions of the TeV blazars requires Bulk Lorentz factors $\geq 25$ [Krawczynski et al. 2001].
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Georganopoulos & Kazanas (2003) and Ghisellini et al. (2005) propose modifications to the simple SSC model. The first authors postulate that the $\gamma$-ray emission originates from a fast jet region with electrons that upscatter low-energy seed photons from the downstream plasma that decelerated from bulk Lorentz factors $\sim 15$ to $\sim 4$. The second authors assume that the jet is composed of a fast spine and a slower envelope. In this model, electrons in the spine emit the $\gamma$-rays by scattering low-energy seed photons from the envelope. In both cases, the relative motion of the fast and slow plasma components boosts the seed photon densities in the reference frame of the fast components. As a consequence, the models are able to describe the data with model parameters that correspond to approximate equipartition between the energy density of relativistic electrons (and/or positrons) and the energy density of the magnetic field.

Recently, various authors emphasized that the detailed geometry of the emission region will impact the observational signatures significantly. Mimica et al. (2005) performed hydrodynamic studies of internal shocks in AGN jets arising from collisions of density inhomogeneities. Sokolov et al. (2005) simulated blazar flares assuming a simple geometry of the jet and the particle accelerating shock, taking into account light travel delays for the photons acting as seed photons for Inverse Compton processes and the photons escaping the emission region. Both studies indicate that simple one-zone models are not able to adequately describe the detailed observational data that have become available during the last several years. It will be a major challenge to find observational signatures that constrain the jet physics while they do not depend on model details. Examples of such a signature are the soft X-ray precursors expected to precede major flares if the jet energy is mainly transported by cold electrons and not by Poynting flux (Moderski et al. 2004).

We have limited the discussion here to leptonic models. Discussions of hadronic models can be found in (Mannheim et al. 1993, Dar & Laor 1997, Pohl & Schlickeiser 2000, Aharonian 2000, Mücke et al. 2003, Atoyan & Dermer 2003, Böttcher 2005, Reimer et al. 2005).

5. Outlook

The sensitivities of the new experiments H.E.S.S., VERITAS, MAGIC and CANGAROO III surpass or will surpass those of the preceding generation (Whipple, HEGRA and CAT) by one order of magnitude. The highest priority of the upcoming observations is to increase the number of TeV detections and to study a larger sample of sources in detail. Using a large statistical sample of sources at different redshifts might allow us to constrain the extent to which the GeV/TeV $\gamma$-ray energy spectra are modified by extragalactic absorption owing to the GeV/TeV photons pair-producing with photons of the Cosmic Infrared Background (CIB). The $\gamma$-ray data may give unique information about the intensity and spectrum of the CIB and may thus constrain the history of star formation in the early Universe (Stecker et al. 1992; Primack et al. 2001; Dwek & Krennrich 2004).
The determination of the modification of the $\gamma$-ray energy spectra by extragalactic absorption is an important pre-requisite for the astrophysical interpretation of the GeV/TeV $\gamma$-ray data. With a better handle on the extent of extragalactic absorption, detailed broadband observations should be able to yield an unambiguous identification of the emission mechanism. Once the emission mechanism is known, the matter, energy content, and structure of the jets can be constrained, and implications for the accretion and jet formation processes can be derived.

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