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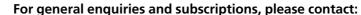
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Very High Energy γ-rays from AGN

Tadashi Kifune

Shinshu University, Wakasato 4-17-1, Nagano, Japan, 380-8553
tkifune@gipwc.shinshu-u.ac.jp

Abstract: Evidence of TeV γ-ray emission has been found for only a handful of active galactic nuclei, with detailed investigations limited to the blazars Mrk 421 and Mrk 501. TeV γ-ray astronomy, as the highest energy band, provides important information that is hard to obtain from longer wavelength electromagnetic radiation. The current status of TeV γ-ray studies of active galactic nuclei is summarized and our understanding of the high energy phenomena taking place in active galactic nuclei is outlined, with the prospects for future TeV γ-ray observations also considered.

Keywords: acceleration of particles — galaxies: active — galaxies: individual (Mrk 421, Mrk 501) — gamma rays: observations — infrared: general

1 Introduction

The detection of GeV γ-ray emission from a large number of active galactic nuclei (AGN), with the EGRET detector on the Compton Gamma Ray Observatory satellite, was a somewhat unexpected result. The third EGRET catalogue (Hartman et al. 1999) lists 66 high confidence detections of AGN, with a further 28 lower confidence potential identifications, placing AGN as the second largest population of sources after the unidentified (but, from their distribution, mostly Galactic) sources. In contrast, TeV γ-rays have been detected from only a handful of AGN. Gamma-ray astronomy at TeV energies is still in its infancy, with the imaging Cerenkov technique having been pioneered a little over 10 years ago. High energy γ-rays provide a *direct* key for understanding blazar phenomena, particularly about the processes in which high energy particles play a major role. TeV γ-ray outbursts from Mrk 421 and Mrk 501 have been investigated by multi-wavelength campaigns to uncover the acceleration mechanism for the energetic particles which are responsible for the radiation, and to estimate the magnetic field strength and the beaming factor δ of the relativistic jet.

Radiation of high energy γ-rays is due to non-thermal, energetic particles. The high energy particles are believed to eventually escape from their acceleration site and to contribute to the cosmic ray flux, which has a power law energy spectrum extending from GeV energies to well beyond TeV energies. Gamma-ray astronomy was originally motivated by the belief that γ-ray sources would indicate the acceleration site of cosmic rays, which extend to the highest particle energies in the present universe. Observation of γ-rays at higher energies provides a direct method of determining the maximum energy to which the particles are accelerated. The particle reactions at extremely high energies may in principle be related to unknown, exotic processes, and investigation of energetic phenomena using high energy γ-rays provides a means of probing this possibility.

The highest energy electromagnetic radiation currently employed for astronomy is provided by VHE (very high energy) γ-rays at TeV energies, which are detected in ground-based observations using the atmospheric Cerenkov technique. The non-thermal power spectrum, or the number flux of γ-ray photons from blazars, decreases rapidly with increasing photon energy. Thus, γ-ray astronomy needs a larger detection area at higher γ-ray energy. The ground-based detection of TeV γ-rays is possible because of the huge effective detection area of $\sim 10^4\,\mathrm{m}^2$ that results from the Cerenkov light pool due to from the passage of TeV γ-ray initiated cascades through the atmosphere. However, the flux sensitivity is still low and the outcome from current observations is biased towards states of higher activity of AGN. Efforts to achieve improved sensitivity are underway, using systems of multiple telescopes, such as CANGAROO III in Australia, the HESS project in Namibia, and VERITAS in USA, or using a large single telescope, such as MAGIC in the Canary Islands. These systems will be in full operation before the launch of the GLAST satellite scheduled in 2006.

2 Current Status of TeV Blazars

The AGN for which evidence of TeV γ-ray emission has been reported are listed in Table 1. Gamma-ray emission from Mrk 421 and Mrk 501 has been reported by a number of independent groups, with the energy spectra of these two blazars being investigated in detail. The other reported TeV blazars have yet to be independently confirmed. Mrk 421, the first TeV blazar, was discovered as the second TeV source (Punch et al. 1992) after the Crab Nebula. The Whipple group (Kerrick et al. 1993) had observed about 20 AGN (consisting mainly of BL Lac objects and Seyfert galaxies) which included 10 blazars detected by EGRET. After discovering the second TeV blazar, Mrk 501, four years later (Quinn et al. 1996) it took almost two more years before the Whipple group first

Table 1.   **TeV blazars (adapted from from Weekes 2001 and updated)**

Object	Redshift	Year of discovery report	Group	EGRET detection
Markarian 421	0.031	1992	Whipple and many others	yes
Markarian 501	0.034	1996	Whipple and many others	yes
1ES 2344+514	0.044	1998	Whipple	no
1ES 1959+650	0.048	1999	Telescope Array	no
PKS 2155−304	0.116	1999	Durham	yes
1H 1426+428	0.129	2001	Whipple and HEGRA	no
3C66A	0.44	1998	Crimea	yes

observed episodic high activity in 1997. A dramatic outburst of Mrk 421 was observed by the Whipple Telescope in May 1996 (Gaidos et al. 1996) with a flare duration of only 15 minutes.

Episodic outbursts have allowed us to study Mrk 421 and Mrk 501 in some detail. On the other hand, the case of 1ES 2344+514 (Catanese et al. 1998) is a good example of the limits of the current sensitivity of TeV observations. The detected count rate was ~ 1 per minute, corresponding to $\sim 10^{-11}$ erg cm^{-2} s^{-1}, similar to the flux of Mrk 501 when it was discovered. This relatively weak flux requires a considerable amount of observation time for both the initial detection and then later confirmation. If the discovery was made during a higher-than-average flux state for the source, efforts to confirm the discovery are likely to be frustrated, as has indeed been the case for 1ES 2344+514 to date. Thus, the current knowledge of TeV blazars is biased to flaring states with count rates much higher than ~ 1 count per minute.

The high active state of Mrk 501 in 1997 continued for several months. Many northern hemisphere groups were able to participate in multi-wavelength campaigns, from radio frequencies to GeV γ-rays. An EGRET detection of Mrk 501 at this time established it also as a GeV γ-ray blazar. TeV γ-rays observations provided data on time scales from hours to months. From January to March 2001, Mrk 421 was in a highly active state. A very intense outburst, with a counting rate of ~ 12.5 γ-ray photons per minute enabled the Whipple group to measure the energy spectrum from 260 GeV to 17 TeV with a statistical error at the 2% level, and to determine the spectral shape as

$$\frac{dN}{dE} \propto E^{-2.14 \pm 0.03} \times e^{-E/E_0} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1},$$

where the cutoff energy $E_0 = 4.3 \pm 0.3_{\text{stat}} (-1.4 + 1.7)_{\text{syst}}$ TeV (Krennrich et al. 2001). The CANGAROO group based in South Australia undertook observation at large zenith angles and detected the source with comparatively good statistics at energies beyond 10 TeV (Okumura et al. 2001).

The shape of the energy spectrum around ~ 10 TeV was measured also for Mrk 501 from the data during the 1997 flare, making possible an interesting comparison with the active state of Mrk 421. If the apparent shape and cutoff energy of the spectra are intrinsic to each individual AGN, an important clue is given to understanding the shock acceleration mechanism of high energy particles in the AGN jet. Alternatively, E_0 may have a common value, determined by the absorption when TeV γ-rays encounter infrared background photons. The comparison by the Whipple group shows that the two cutoff energies are consistent with each other but that a different spectral index is required for an acceptable fit to the Mrk 501 data (Krennrich et al. 2001).

A systematic study of EGRET blazars by multi-wavelength observations from radio through X-rays to γ-rays has indicated (Ghisellini et al. 1998) that the blazars having higher energy inverse Compton peaks, or higher acceleration energies, have lower bolometric luminosities. This is consistent with the fact that Mrk 421 and Mrk 501 are among the weakest GeV sources. The current number of TeV blazars is too small to allow us to argue about consistency with such a tendency among the TeV γ-ray blazars. However, it is notable that the behaviour of Mrk 421 and Mrk 501 during the flares is very different. The peak energy of synchrotron radiation increases with the strength of the outburst in the case of Mrk 501, i.e. there is a spectral hardening of TeV γ-rays, while for Mrk 421 the peak energy, or the maximum acceleration energy of electrons, stays almost constant. This fact suggests that there may be other TeV blazars which have properties quite different from these two well-studied blazars. A larger number of TeV sources is required to obtain a better understanding of TeV blazars.

3 Characteristics of TeV γ-rays and Blazars

Photon–photon interactions take place when the wavelength becomes short enough to create an electron–positron pair. The cross section of the process,

$$\gamma + \text{soft photon} \rightarrow e^+ + e^-,$$

takes the maximum value near the threshold energy, which is given by

$$\epsilon_\gamma \epsilon = m_e^2 c^4 \approx (5 \cdot 10^5 \text{ eV})^2,$$

where ϵ_γ and ϵ are the energy of γ-ray and target soft photons. VHE γ-rays suffer from absorption when they encounter ambient radiation fields of soft photons with wavelengths $\sim 1\,\mu$m or photon energies of ~ 1 eV. Photons of GeV γ-rays can be also absorbed in interactions

with X-rays. However, the density of X-ray photons is generally much lower than that of infrared radiation. Thus, the process is much more prominent at γ-rays of energies above ~ 1 TeV. The sources of TeV γ-rays must also be optically thin to this absorption, giving constraints to the size of the emission region and the distance from the Earth.

3.1 Interaction with Infrared Background Radiation

The mean free path of TeV γ-rays is estimated to be about 100 Mpc, since the intensity of infrared background radiation is $\sim (1-10)$ cm^{-3}, and the cross-section of pair creation is roughly given by the Thomson cross-section, σ_T, of $\sim 10^{-25}$ cm^2. The mean free path thus limits detectable TeV γ-ray fluxes to relatively nearby AGN, which is consistent with the fact that the two firmly established TeV AGN, Mrk 421 and Mrk 501, are located at redshifts of ~ 0.03.

The absorption of TeV γ-rays causes a cutoff in the energy spectrum. The cutoff energy will vary as a function of the distance to the object, appearing at lower energies for the blazars at greater distances. The intensity of the IR background radiation is, however, not known well enough to determine the precise correction for the absorption effect on the energy spectrum. Conversely, from TeV data, a constraint can be set on the background IR radiation, and the possibility of determining the IR intensity in this way is one of important outcomes from observations of blazars at TeV energies. The next generation of ground-based γ-ray telescopes will have lower energy thresholds, and are expected to detect more TeV blazars at greater distances than the current telescopes.

The energy spectrum of Mrk 421 and Mrk 501 has been measured up to about 10 TeV as mentioned in the previous section. During the outburst in 1997, Mrk 501 showed an interesting feature of higher peak energy of synchrotron X-rays. The TeV γ-ray spectrum was measured up to about 20 TeV (Samuelson et al. 1998; Aharonian et al. 1999; Djanatti-Atai et al. 1999; Aharonian et al. 2001a), and the observed spectrum must have been considerably attenuated. In order to infer the intrinsic energy spectrum from the blazar, the energy spectrum observed must be corrected for the absorption. Applying this correction using the relatively intense IR background radiation reported by Finkbeiner, Davis, & Schlegel (2000) results in an unusual up-turn in the intrinsic TeV spectrum, i.e. a seemingly unphysical increase in the flux at higher energies (Protheroe and Meyer 2000).

The strength of the background IR radiation can be studied by the possible formation of a *pair halo* around distant TeV sources (see, for example, Aharonian, Coppi, & Völk 1994), arising from VHE γ-ray emission of the electrons and positrons produced in the TeV γ-ray absorption. A detectable flux of TeV γ-rays might be radiated from the electrons and positrons, and evidence of such emission from the pair halo can be given from detecting the persistent nature in time as well as from the angular distribution as a halo around the direction of TeV blazars. The obtained limit on the halo flux above 1 TeV from

Mrk 501 within $0.5°-1°$ is $10^{-12}-10^{-11}$ cm^{-2} s^{-1} (90% confidence level), between 0.1% and 1% of the peak burst flux during the 1997 outburst (Aharonian et al. 2001b). The estimate of halo flux and angular distribution is highly dependent on unknown parameters such as the strength of the magnetic field in intergalactic space. The halo emission has an interesting possibility of extending TeV γ-ray studies of blazars; the relatively time-invariant nature of the halo flux is an average over all TeV outbursts in the past, providing an alternative way of estimating all the bursts unobserved and of detecting blazars at distances beyond the horizon of unattenuated TeV γ-ray emission.

3.2 Absorption of TeV γ-rays and Size of Radiation Region

The spatial size of the emission region is a parameter of prime importance in estimating how near to the presumed massive black hole the phenomena are taking place. Whereas the time scale of variability sets an upper bound on the size, the detection of TeV γ-rays can in addition provide a lower bound. Since TeV γ-rays must escape absorption by electron–positron pair creation, the optical depth of the radiation region is not likely to exceed unity. A constraint is thus set on the size of the emission region as a function of beaming factor δ. The beaming factor and spatial size can be inferred model independently, as a result of observations of TeV γ-rays outbursts. The shortest duration TeV flare observed to date is 15 minutes, for Mrk 421 (Gaidos et al. 1996). However, the detectable duration time can be biased by the intensity of the flare, as outbursts shorter than 15 minutes with less intense fluxes would be difficult to detect with the current generation of telescopes.

3.3 Hadronic Interactions and Higher Energies

The total energy that the AGN jet carries is not well known in spite of its importance. The estimation varies greatly if the jet consists of hadrons rather than a pair plasma of electrons and positrons. However, electromagnetic radiation at wavelengths longer than γ-rays is almost blind to high energy protons, since the radiation from protons is due to the production of neutral pions which decay into two γ-rays of energies higher than about 100 MeV.

The total power is conventionally estimated by presuming that the equipartition of energies holds between the magnetic field and electrons as well as protons. Recent detailed investigations of the component of inverse Compton peak by γ-rays has presented a direct means of estimating the magnetic field, and deviations from equipartition can occur; the energy density of magnetic field can be an order of magnitude less than that of relativistic electrons (Takahara, Kino, & Kusunose 2001).

Hadron progenitors for the inverse Compton peak, if true, alters the view based on the energy of electrons as well as positrons and magnetic field, and thus it is quite important to know the contribution of high energy protons. In addition, the shock in the jet may accelerate protons

up to $\sim 10^{20}$ eV, the highest observed cosmic ray energies. Such energetic protons emit γ-rays at TeV energies by synchrotron radiation (Aharonian 2000; Mücke and Protheroe 2001).

Such a process would also influence the interpretation of the unusual spectrum shape at energies higher than TeV, i.e. the possible up-turn in the energy spectrum. It is necessary to extend observations of the energy spectrum up to the energy beyond 50 TeV, where it has been speculated that exotic processes may become apparent (e.g. Kifune 1999; Harwit, Protheroe, & Biermann 1999).

4 Discussions and Summary

The detailed study of TeV blazars is so far limited to only two objects: Mrk 421 and Mrk 501. These both have a redshift of $\approx$0.03, however interesting differences have been found between the two TeV blazars. The energy spectrum appears to become harder during outbursts with increasing luminosity in Mrk 501, consistent with the peak energy of synchrotron radiation detected at X-ray energies, shifting higher during outbursts, while, in the case of Mrk 421, the peak energy stays almost constant. Such a relation of increasing peak energy with increasing luminosity is opposite to the tendency that brighter GeV blazars seem to have a lower maximum energy of accelerated electrons.

Investigations of X-ray data suggest that more TeV blazars exist. Among the new 'extreme' BL Lac objects with high synchrotron peak frequencies found by Costamante et al. (2001), 1H 1426+428 was recently reported to emit TeV γ-rays of the differential flux at 430 GeV of $2.9 \pm 1.1 \times 10^{-11}$ cm^{-2} s^{-1} TeV^{-1} with $>4\sigma$ significance (Horan et al. 2001). The object has a redshift of 0.129, significantly larger than those of Mrk 421 and Mrk 501, and is thus expected to provide sensitive new data relevant to the absorption of TeV γ-rays against the infrared background radiation.

The general tendency indicated from EGRET detected blazars (Ghisellini et al. 1998) is interpreted that the change of the maximum energy of electrons is determined by variation of energy loss, i.e. the energy density of the magnetic field as well as the external radiation field. Such a widely accepted view itself does not explain the fact that the velocity of the jet of Mrk 421 seems to be slower, or more quickly decelerated, when compared with the case

of GeV blazars (Piner et al. 2001). It increases the importance of determining what differentiates the TeV blazars from GeV blazars: it is expected that the next generation of TeV telescopes will, by increasing the number of detected TeV blazars, improve our understanding of AGN.

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