TeV γ-ray Astronomy in the new Millennium

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Abstract. The field of TeV gamma-ray astronomy is reviewed with emphasis on its relation to the origin of cosmic rays. The discovery of TeV photons from supernova remnants and active galaxies has provided the first direct observational link between specific astrophysical objects and particle production at the TeV scale. TeV γ-ray observations constrain the high end of the electromagnetic spectrum, a regime most sensitive for testing particle acceleration and emission models. TeV telescopes have made important contributions to the understanding of blazars and supernova remnants, however, it will take the next generation atmospheric Cherenkov telescopes and satellite-based γ-ray detectors to unravel the mystery of hadronic cosmic-ray sources.

A short review of TeV observations is followed by a discussion of the capabilities and scientific potential of the next generation ground-based atmospheric Cherenkov telescopes.

1. Introduction

Very High Energy γ-ray astronomy (VHE defined as the energy range of 200 GeV - 50 TeV) has extended the photon spectrum of high energy astrophysics of galactic and extragalactic sources through adding a new observational window. Imaging atmospheric Cherenkov telescopes$^1$ have taken the lead in this energy range because of their large collection area ($10^4 - 10^5$ m$^2$), good sensitivity, high angular resolution, good energy resolution and low energy threshold (Ong 1998). The scientific objectives for exploring the universe with VHE photons can be summarized as follows:

I. One of the long standing prime objectives for VHE γ-ray astronomy is to find the sources of cosmic rays. Cosmic rays can be traced through their interactions with matter and subsequent γ-ray emission via π$^0$ production. Where and how does nature accelerate particles to energies that extend to $10^{20}$ eV and beyond?

II. The sky above 10 GeV is still largely unexplored. This is one of the last regions of the astrophysical electromagnetic spectrum with the benefit of the unknown - less than a percent of the sky has been scanned with highly sen-

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$^1$CANGAROO, CAT, Durham, HEGRA, Whipple and Telescope Array, for an overview see Catanese & Weekes (2000)
VHE telescopes. It is important to realize that VHE γ-ray telescopes enter a regime of particle physics phenomena that is complementary to accelerator laboratories: a) Annihilation lines from supersymmetric particle decays constitute an exciting possibility for astroparticle physics\(^2\); b) Probing quantum gravity effects of photons traveling cosmological distances have been suggested (Amelino-Camelia et al. 1998; Biller et al. 2000). c) Also searches for primordial black holes with future imaging atmospheric Cherenkov telescopes have been revived (Krennrich, Le Bohec & Weekes 2000).

III. At lower energies, observations of HE γ-rays (20 MeV - 20 GeV) with the EGRET telescope on-board of the Compton Gamma Ray Observatory, have revealed more than 270 sources (Hartmann et al. 1999): 7 pulsars, 66 high-confidence blazars, 27 lower-confidence blazar identifications, 170 sources not yet identified with known objects (EGRET unidentified sources). It is apparent that the high energy universe is not as sparsely populated as early measurements in the 1960s and 1970s with less sensitive first generation space telescopes OSO-3 (Kraushaar et al. 1972), SAS-2 (Derdyn et al. 1972; Fichtel et al. 1975) and COS-B (Searsi et al. 1977) indicated. The future generation space telescope (Gamma Ray Large Area Space Telescope: GLAST) is expected to detect in the order of \(10^4\) sources (Michelson et al. 1999), with a wealth of GeV γ-ray astrophysics to be explored. A major objective of VHE γ-ray astronomy is to extend observations of the electromagnetic universe to higher energies, to arrive at a more complete picture of the non-thermal leptonic component in astrophysical objects.

In this paper I emphasize point I. and elude to the search for evidence for cosmic-ray hadron acceleration in sources and potential sources of VHE γ-ray emission. Recent observations and some selected results relevant to particle acceleration are summarized in section 2. In section 3, I discuss the next generation atmospheric Cherenkov telescopes, their capabilities and their prospects for establishing astrophysical sites of particle acceleration, in particular sources of nucleonic cosmic-rays.

To date, imaging atmospheric Cherenkov telescopes provide a source catalog (Table 1) consisting of 12 sources (see also Weekes 2000): 2 high confidence plerions, 1 lower-confidence plerion, 2 high confidence blazars, 4 lower-confidence blazar identifications, 3 lower-confidence shell-type supernova remnants. Despite the small number of sources at \(E \geq 200\) GeV, some of the observations (Crab, Markarian 421 and Markarian 501) have revealed statistically strong detections\(^4\) with profound and surprising implications.

To answer the question, as to why so few of the EGRET sources have been seen at TeV energies, it is useful to consider galactic and extragalactic sources separately. Pulsars and unidentified galactic EGRET sources possibly undergo

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\(^2\)A sensitive detector is defined in this paper as an instrument capable of detecting the Crab Nebula in a few hours of observation at the \(> 5\sigma\) level.

\(^3\)Neutralino annihilation of astrophysical origin has been recently reviewed by Bergström et al. 1998 as a possible test to constrain supersymmetric particle theory.

\(^4\)During flaring activity of Markarian 421 and Markarian 501 detections at the 20 - 40 \(\sigma\) level were achieved per night in a few hours of observation (Gaidos et al. 1996; Quinn et al. 1999).
| Source            | Energy (GeV) | Flux ($\times 10^{-11}$ cm$^{-2}$s$^{-1}$) | Group                          | EGRET source |
|------------------|--------------|------------------------------------------|--------------------------------|---------------|
| **Plerions**     |              |                                          |                                |               |
| Crab Nebula      | 400          | 7.0                                      | Whipple, ASGAT, HEGRA, Themistocle, *Gamma, TA, Crimea, CAT, CANGAROO  | pulsed, unpulsed |
| PSR 1706-44      | 1000         | 0.8                                      | CANGAROO, Durham               | pulsed        |
| Vela             | 2500         | 0.29                                     | CANGAROO                       | pulsed        |
| **Shell-type SNRs** |         |                                          |                                |               |
| SN 1006          | 1700         | 0.46                                     | CANGAROO                       | no            |
| RXJ1713.7-3946   | 1800         | 0.53                                     | CANGAROO                       | no            |
| Cassiopeia A     | 1000         | -                                        | HEGRA                          | no            |
| **Blazars: XBL** |              |                                          |                                |               |
| Markarian 421    | 260          | variable                                 | Whipple, HEGRA, CAT            | yes           |
| z = 0.031        |              |                                          |                                |               |
| Markarian 501    | 260          | variable                                 | Whipple, HEGRA, CAT, TA        | no            |
| z = 0.034        |              |                                          |                                |               |
| 1ES2344+514      | 300          | variable                                 | Whipple                        | no            |
| z = 0.044        |              |                                          |                                |               |
| PKS2155-304      | 300          | variable                                 | Durham                         | yes           |
| z = 0.116        |              |                                          |                                |               |
| 1ES1959+650      | 600          | variable                                 | TA                             | no            |
| z = 0.048        |              |                                          |                                |               |
| **Blazars: RBL** |              |                                          |                                |               |
| 3C66A            | 900          | variable                                 | Crimea                         | yes           |
| z = 0.44         |              |                                          |                                |               |
an intrinsic cutoff at the γ-ray production site (e.g., Daugherty & Harding 1996 and references therein; Grenier 1999). For galactic EGRET sources to become detectable with atmospheric Cherenkov telescopes and take advantage of their large collection area, the energy threshold of those has to be lowered, ideally down to the high end of EGRET energies (10 GeV). The non-detection of most EGRET blazars, might be related to an intrinsic cutoff and/or the transparency of the universe on extragalactic distance scales due to the interaction of TeV photons with the infrared background photons via \( \gamma \gamma \rightarrow e^+e^- \). However, the universe for redshifts of \( z \leq 1 \) becomes essentially transparent for photon energies \( E \leq 40 \) GeV (Stecker 2000), showing the need to lower the energy threshold of atmospheric Cherenkov telescopes to the 50 GeV range.

2. Observations:

2.1. Galactic Sources: Supernova Remnants - Plerions

Plerions constitute a class of supernova remnants, that contain a young pulsar with a large spin-down rate that powers a synchrotron nebula through the injection of relativistic particles (Harding 1996). At VHE energies three plerions have been detected: the Crab Nebula, Vela and PSR1706-44. For all three sources the emission is not pulsed and it appears to be constant. This is different from observations at GeV energies, where EGRET observed predominantly pulsed emission (Thompson et al. 1997). With the GeV observations testing the particle acceleration process near the pulsar magnetosphere and the VHE observations constraining the particle energy distribution and magnetic field in the surrounding nebula, both are important for the understanding of pulsars.

\textit{Crab Nebula:} The first unequivocal detection of VHE photons from the Crab Nebula (Weekes et al. 1989) has established the feasibility of the ground-based detection of VHE γ-rays. Production of HE (unpulsed component at \( E \geq 1 \) GeV) and VHE photons can be explained as inverse Compton scattering by relativistic electrons of target photons from synchrotron radiation (synchrotron self-Compton: SSC) and/or ambient infrared and microwave background photons (inverse Compton: IC). Because of its strong synchrotron luminosity (X-rays) and strong magnetic field (fairly young pulsar), the VHE γ-ray flux from the Crab Nebula is attributed dominantly to SSC emission (e.g., De Jager & Harding 1992; Harding 1996).

VHE observations can yield important information about the energy spectrum of the electrons, thus constraining the particle acceleration mechanism, e.g., the maximum electron energy. VHE data (Hillas et al. 1998) together with EGRET data (De Jager et al. 1996) and X-ray spectra (see references in Hillas et al. 1998) have been used to estimate the average magnetic field strength in the X-ray nebula. A magnetic field of 160 µG seems to provide the best fit to the multiwavelength spectrum (Figure 1) between X-ray to several TeV energies (Hillas et al. 1998). In a recent paper by Aharonian et al. (2000a) a magnetic field strength of \( (170 \pm 30) \) µG has been derived, confirming the previous result. The synchrotron self-Compton model also allows the derivation of the maximum electron energy (De Jager & Harding 1992) of \( E_{\text{max}} \sim 10^{16} \) eV.
Figure 1. Whipple (Hillas et al. 1998) and EGRET (Nolan et al. 1993) measurements of the Crab Nebula $\gamma$-ray spectrum in the HE - VHE regime are shown. The dotted line is a fit to the Whipple and EGRET fluxes using an SSC-model fitting the X-ray and $\gamma$-ray spectrum consistently under the assumption of an average magnetic field of 160 $\mu$G in the X-ray nebula (Hillas et al. 1998).
No evidence for $\gamma$-rays from $\pi^0$ decays is present in the data. If protons were accelerated in the Crab Pulsar (Atoyan & Aharonian 1996; Bednarek & Protheroe 1997), they could make a noticeable contribution to the $\gamma$-ray flux above 10 TeV, a regime where synchrotron cooling and the energy dependency of the Klein-Nishina cross-section steepens the SSC contribution.

The measurement of the Crab spectrum above 10 TeV can be most efficiently addressed using the large zenith angle technique (Krennrich et al. 1997; Krennrich et al. 1999a; Tanimori et al. 1999; Aharonian et al. 2000a). A dedicated program over the typical lifetime (5 years) of one of the future telescope arrays (VERITAS) could achieve a high precision spectrum of the Crab Nebula between 50 GeV and 50 TeV.

At the low energy end, a recent detection of 50 GeV photons from the Crab Nebula by the CELESTE collaboration (De Naurois et al. 2000) using an array of heliostats as a $\gamma$-ray telescope emphasizes the progress that has been made in closing the energy gap between satellite instruments and ground-based telescopes. The Crab Nebula will play an important role in cross-calibrating future ground-based $\gamma$-ray telescopes located in the northern hemisphere (MAGIC, VERITAS) with GLAST.

In summary, the Crab Nebula although not favored as an acceleration site of hadronic cosmic rays, is an important testbed and calibration source for models (in particular SSC) of $\gamma$-ray production and for searching for a hadronic component at $E > 10$ TeV.

Other plerions: Vela, PSR 1706-44  Vela (Yoshikoshi et al. 1997) and PSR 1706-44 (Kifune et al. 1995; Chadwick et al. 1997) have been detected in VHE $\gamma$-rays. The VHE $\gamma$-rays from the direction of $\gamma$-ray pulsar PSR 1706-44 could be associated with a surrounding nebula similar to the Crab Nebula. However, the emission is likely due to inverse Compton scattering of electrons off the 2.7 K cosmic microwave background radiation. Since unpulsed X-ray emission has been observed by ROSAT (Becker et al. 1994) a plerion with a weak magnetic field seems a reasonable explanation for the VHE emission from PSR 1706-44. Plerions with a weak magnetic field could become standard candles in the HE - VHE $\gamma$-ray regime to test models involving IC scattering on the cosmic microwave background.

2.2. Galactic Sources: Pulsars

A major distinction between pulsar models is whether the pulsed $\gamma$-ray emission is produced by particles accelerated near the polar cap (Daugherty & Harding 1996) or in the outer magnetosphere (Cheng, Ho & Ruderman 1986; Romani 1996). Both mechanisms result in $e^+e^-$ pairs, which produce synchrotron radiation and, via Compton scattering, boost soft photons to high energy $\gamma$-rays. If VHE photons were produced near the polar cap, they would produce $e^+e^-$ on the strong magnetic fields, precluding the detection of VHE $\gamma$-rays. Therefore, if TeV pulsations are observed, then pulsed emission must have its origin relatively far from the neutron star surface, e.g., in the outer magnetosphere, supporting the outer gap model.
Crab, Geminga, Vela, PSR B1951+32: EGRET has detected at least 6 pulsars: Crab, Geminga, Vela, PSR B1951+32, PSR1706-44, PSR B1055-52 (Thompson 1997). Searches for pulsed emission at VHE energies from the Crab Nebula (Lessard et al. 2000; Aharonian et al. 1999a), Geminga (Akerlof et al. 1993; Aharonian et al. 1999a), the Vela pulsar (Yoshikoshi et al. 1997), PSR1509-58 (Sako et al. 2000) and PSR B1951+32 (Srinivasan et al. 1997) have yielded null results. EGRET data of PSR B1951+32 in fact shows a rising spectrum indicating that the maximum power occurs at several GeV. The Whipple upper limit (Srinivasan et al. 1997) to the pulsed flux ($E > 260$ GeV) is two orders of magnitude below the extrapolated EGRET spectrum setting the most severe constraint on the outer gap model (Cheng, Ho & Ruderman 1986). Instruments with a lower energy threshold ($< 50$ GeV) are required (De Jager 2000) to constrain the apparently sharp cutoff in pulsars through a measurement of the pulsed $\gamma$-ray spectrum.

2.3. Galactic Sources: Shell-type Supernova Remnants

Supernovae are the primary candidates held responsible for the flux of hadronic cosmic rays up to energies of approximately $Z \times 10^{14}$ eV ($Z =$ nuclear charge or particle) for two reasons: 1. they appear to be the only galactic objects capable of supplying the power required for the cosmic-ray energy density in our galaxy, 2. a theory of diffuse shock acceleration (Blandford & Ostriker 1978; Bell 1978; Legage & Cesarski 1983) does produce a power-law spectrum of $dN/dE \propto E^{-2.1}$. This would be consistent with the observed local cosmic ray spectrum $dN/dE \propto E^{-2.7}$, after correcting for galactic diffusion by $\propto E^{-0.6}$ (Swordy et al. 1990). Biermann & Strom (1993) suggest a primary source spectrum somewhat steeper ($dN/dE \propto E^{-2.33}$) requiring a factor of $dN/dE \propto E^{-0.3}$ for galactic leakage.

It was suggested (Drury, Aharonian & Völk 1994; Naito & Takahara 1994) that observations of HE - VHE $\gamma$-rays, due to collisions of cosmic ray nuclei with the interstellar medium via $\pi^0$ production, could provide the crucial evidence for cosmic-ray acceleration in shell-type supernova remnants (SNRs). The $\gamma$-ray spectrum would reflect the spectral index of the cosmic-ray spectrum at the source. A clear indication for acceleration of nuclei in SNRs would be the $\pi^0$ bump at low energies with the spectrum extending to ten's of TeV, assuming the background from the galactic plane diffuse $\gamma$-ray emission can be separated from the SNR.

However, experimentally the situation is complicated by a possible inverse Compton $\gamma$-ray component from VHE electrons boosting 2.7 K microwave background photons to TeV energies. In order to establish $\gamma$-rays with $\pi^0$ origin in supernova remnants, the contribution from electrons has to be subtracted. This will require to measure the $\gamma$-ray energy spectrum over a wide energy range, ideally from 10 MeV - 10 TeV.

SN 1006, RXJ1713.7-3946: Recently the CANGAROO collaboration has reported the detection of $\gamma$-rays from two shell-type SNRs - SN 1006 (Tanimori et
al. 1998b) and RXJ1713.7-3946 (Muraishi et al. 2000). These observations still require confirmation and the measurement of energy spectra, accurate enough to distinguish a spectral index (2.1) for diffuse shock acceleration (Blandford & Ostriker 1978; Bell 1978; Legage & Cesarski 1983) from other scenarios.

To date, these detections prove to be inconclusive as to whether or not shell-type SNRs accelerate hadronic cosmic rays (Aharonian & Atoyan 1999: Baring 1999). The reason is, that the origin of the TeV photons can be linked to the X-ray emission in these objects. The discovery of non-thermal X-ray emission in SN 1006 provided the first unambiguous evidence for electrons with energies up to 100 TeV in SN 1006 (Koyama et al. 1995). Similarly SNR RXJ1713.7-3946 was recently discovered as an X-ray source in ROSAT and ASCA data (Pfeffermann & Aschenbach 1996).

Therefore, VHE photons detected from SN 1006 and RXJ1713.7-3946 may well arise from VHE electrons via inverse Compton scattering against low energy photons (2.7 K). In fact, VHE emission from SN 1006 had been suggested by several theorists (Pohl 1996; Mastichiadis 1996; Mastichiadis & de Jager 1996; Yoshida & Yanagita 1997) based on this picture using the X-ray luminosity and an equipartition magnetic field estimate. Conversely, the VHE flux together with the X-ray flux from SN 1006 provides an estimate of the magnetic field strength in the X-ray shell, yielding a value of $6.5 \pm 2 \mu G$ (Tanimori et al. 1998b). A hadronic component is however not ruled out, but might be difficult to distinguish from the IC component based on the VHE spectrum alone (Aharonian & Atoyan 1999). These authors suggest that spatially resolving the VHE emission region to search for correlations with matter density might become an important tool in settling the question whether or not hadronic processes play a significant role.

Another example of a shell-type supernova remnant with a potentially strong inverse Compton component is RXJ1713.7-3946 because it has been detected in X-rays (Pfeffermann & Aschenbach 1996) showing a non-thermal emission in the shell. A detection of VHE photons has been reported by Muraishi et al. (2000). Under the assumption that the origin of the TeV photons is related to IC scattering of electrons on the microwave background radiation, a magnetic field of $11 \mu G$ was estimated.

**IC443, γ-Cygni, W44, W51, W63 and Tycho:** Neither SN 1006 nor RXJ1713.7-3946 were on the top of the list of good candidates for searching for VHE emission from neutral pions in shell-type SNRs. This is different for a set of SNRs chosen by Buckley et al. (1998): IC443, γ-Cygni, W44, W51, W63 and Tycho. Among other criteria, the latter were selected with view for an enhanced $\pi^0$ component through a possible association with a molecular cloud. Most importantly, γ-Cygni, W44 & IC443 show a possible association with EGRET sources: the positions of 3 unidentified EGRET sources are consistent with these shell-type SNRs (Stturner & Dermer 1995; Esposito et al. 1996; Lamb & Macomb 1997; 5It should be noted that that observations (Chadwick et al. 1999) with the Durham Mark VI telescope set an upper limit on this source conflicting with the CANGAROO observation. For further details see Weekes (1999).
Jaffe et al. 1997). However, because of EGRET’s limited angular resolution a clear identification cannot be made.

Following Buckley et al. (1998), by assuming that the EGRET emission is from these shell-type SNRs and that \( \gamma \)-ray emission comes dominantly from \( \pi^0 \)'s, the spectral index for these SNRs would have to be softer (2.5 for \( \gamma \)-Cygni, 2.4 for IC443) than predicted by Drury, Aharonian & Völk (1994). Gaisser, Protheroe & Stanev (1998) performed multiwavelength fits to the EGRET data and Whipple upper limits. They find that a differential spectral index of nuclei and electrons (assuming electrons and nuclei are accelerated with the same spectral indices) is \( \sim 2.2 \) - 2.4 (Gaisser, Protheroe & Stanev 1998).

**Cas-A:** A high X-ray flux and a hard spectrum (Allen, Gotthelf & Petre 1999) and the relatively high ambient matter density makes Cas-A an example of a shell-type supernova remnant that might exhibit both, a strong IC and/or a high \( \pi^0 \) \( \gamma \)-ray component. HEGRA presented evidence for VHE emission from Cas-A (Pühlhofer et al. 1999) at the 3.4 - 4.5 \( \sigma \) level, however, verification of the result will be required.

GLAST and future ground-based Cherenkov telescopes will provide unambiguous source identification and measurements of the energy spectra with high sensitivity. GLAST at the low end of the spectrum could see the \( \pi^0 \) bump (Ormes, Digel, Moskalenko & Williamsen 1999) which could provide evidence for acceleration of hadronic nuclei. However, the background from the diffuse galactic plane emission also exhibits a \( \pi^0 \) bump, making this signature ambiguous. TeV telescopes could measure the spectrum between 50 GeV up to ten’s of TeV providing together with GLAST a spectral constraint between 10 MeV - 50 TeV. Together with the X-ray spectrum this could provide the spectral data necessary to untangle the IC from the nucleonic components. Furthermore spatial correlations with X-ray emission could trace the IC component whereas a correlation with matter density could trace the nucleonic component.

### 2.4. Galactic Plane:

Cosmic rays interacting with the interstellar medium (ISM) give rise to the emission of \( \gamma \)-rays over a wide range of energies. The processes considered are bremsstrahlung, inverse Compton scattering, and the \( \pi^0 \) production via hadronic interactions of protons and nuclei; however, the magnitude of their individual contributions to the observed \( \gamma \)-ray flux has become a matter of debate. In the COS-B era, the situation appeared fairly non-controversial with the \( \gamma \)-ray emission (Mayer-Hasselwander et al. 1982) matching the model by Bertsch et al. (1993) well without major discrepancies between observations and theory.

This has changed with EGRET observations. Although, the EGRET data show good spatial agreement with model calculations, at energies above 1 GeV the observed intensity surprisingly exceeds the model prediction by 60% (Hunter et al. 1997). Various suggestions have been made to resolve this discrepancy. Hunter et al. (1997) proposed that the excess is due to unresolved point sources. Pohl et al. (1997) showed that unresolved \( \gamma \)-ray pulsars could significantly contribute to the diffuse galactic emission; however, the latitude distribution for pulsars is too narrow to explain the observed excess.
Figure 2. The energy spectrum of the diffuse galactic plane emission as measured by EGRET (Hunter et al. 1997) is compared to a model (HEMN model) by Strong, Moskalenko & Reimer (2000). This model is based on an electron injection index of $\alpha = 1.8$ ($dN/dE \propto E^{-\alpha}$) and a modified nucleon spectrum. Furthermore, we show the upper limit from Whipple observations (Whipple 2000) of the galactic plane at $l = 40^\circ$, $-2.0^\circ < b < 2.0^\circ$ by Le Bohec et al. (2000).
Attempts to explain the flux at \( E > 1 \) GeV by a harder interstellar proton spectrum (Mori 1997; Moskalenko, Strong & Reimer 1998) than locally observed, are limited by constraints from antiproton and positron measurements (Strong, Moskalenko & Reimer 2000). It has also been suggested (Pohl & Esposito 1998), that the interstellar electron spectrum can be harder than that locally observed, allowing a significant inverse Compton contribution at higher energies. A recent study (Strong, Moskalenko & Reimer 2000) shows in fact that a harder electron spectrum (injection index 1.8) and a modified nucleon spectrum (in agreement with antiproton and positron flux constraints) can fit the data between 10 MeV - 30 GeV reasonably well (see Figure 2). Given the hard \( \gamma \)-ray spectrum above 1 GeV the prospects for detecting the diffuse emission from the galactic plane at 100’s of GeV with ground-based Cherenkov telescopes are promising if the spectrum extends. Observations by the Whipple collaboration (Le Bohec et al. 2000) have provided an upper limit that is close to the extrapolation of the EGRET spectrum. These data resulted in a lower limit of \( \alpha = 2.31 \) (\( dN/dE \propto E^{-\alpha} \)) on the differential spectral index (Figure 2), assuming there is no break in the spectrum between 30 - 500 GeV. The Whipple upper limit at 500 GeV, provides strong evidence that, if the excess at GeV energies is due to an IC component from electrons, either the electron spectrum undergoes a sharp intrinsic cutoff at the acceleration site, or cooling processes result in a spectral break.

2.5. Extragalactic Sources: Blazars

Active galactic nuclei (AGNs) observed at \( \gamma \)-ray energies of \( E > 100 \) MeV are believed to exhibit highly anisotropic radiation along their jets. Those with their jet axis closely aligned with the observer’s line of sight are collectively called blazars and include optically violent variable quasars, highly polarized quasars and BL Lacertae (BL Lac) objects. Their emission spectrum is dominated by non-thermal emission which spans the entire wavelength range from radio to \( \gamma \)-rays. Short flux variability and dominantly non-thermal emission suggests that the observed radiation in these objects is produced primarily by a jet of highly relativistic particles with the emission region moving at relativistic speed towards the direction of the observer.

This preferred geometry implies that the luminosity in the direction of the jet is greatly enhanced by the 4th power of the relativistic Doppler factor (typically \( \sim 10 \)), making blazars appear even more powerful (Blandford & Rees 1978).

**Variability: Markarian 421, Markarian 501:** VHE observations of Markarian 421 and Markarian 501 have revealed extremely variable \( \gamma \)-ray emission (Gaidos et al. 1996: Quinn et al. 1999). Observations of Markarian 421 on May 7 1996 came as a surprise, showing a flux increase by a factor of 50 reaching a maximum of 10 Crab (flux measured in units of the steady emission from the Crab Nebula) within two hours (Figure 3). A remarkably short doubling and decay time of 15 minutes was observed on May 15 1996. These short flux variations provide information about particle acceleration, energy loss, the emission process in the jet, the bulk Lorentz factor (from \( \gamma\gamma \rightarrow e^+e^- \) opacity argument) and the size of the emission region. The Markarian 421 observations indicate a compact
emission region of 1 - 10 light hours in diameter \((R \leq 10^{-3}\text{ pc})\) corresponding to 10 Schwarzschild radii of a \(10^8\) solar mass black hole (Gaidos et al. 1996).

The location of the emission region could be either close to the supermassive black hole or, in the case of a shock front propagating out along the jet, substantially further out. It is important to note, that the minimum detectable variability time scale is limited by the sensitivity of existing \(\gamma\)-ray detectors, shorter variability time scales cannot be ruled out. One objective of future generation detectors will be to measure the minimum variability time scale, by the means of a lowered energy threshold and increased collection area.

Variability over a wide range of time scales has been observed for the \(\gamma\)-ray emission of Markarian 501. Markarian 501 at the time it was discovered as a \(\gamma\)-ray blazar (Quinn et al. 1996) showed a flux level of \(\sim 7\%\) of the Crab. Figure 4 shows the night by night \(\gamma\)-ray rates between 1995 - 1998 in units of Crab. A variability time scale of a month can be seen in the 1996 data, day-scale variability (up to \(\sim 4\) Crab) can be seen in the 1997 data and even hour scale variability can be seen for two nights in 1997 (Quinn et al. 1999).

The wide range of variability time scales established by these observations naturally raises the question as to what causes these variations and further more, are they of the same origin? Perhaps the most intriguing questions about the particle jet are, what is the acceleration mechanism and which particles are accelerated in the jet: electrons and positrons (collectively called electrons), or protons, or both. In leptonic models of blazars, the main source of \(\gamma\)-rays is Compton scattering of soft photons by energetic electrons in the jet. The source of soft photons could be due to self-synchrotron radiation of the electrons in the jet (Maraschi, Ghisellini & Celotti 1992; Marscher & Bloom 1994), referred to as SSC models. On the other hand, if the soft photons originate from ambient radiation external to the jet, e.g., the accretion disk (Dermer, Schlickeiser & Mastichiadis 1992) or broad-line region clouds (Sikora, Begelman & Rees 1994; Blandford & Levinson 1995). Modelers call those external Compton models (EC).

A source of \(\gamma\)-rays related to cosmic ray acceleration could be due to photo-meson \((p\gamma \rightarrow \pi X)\) or photo-pair \((p\gamma \rightarrow e^\pm X)\) production of high energy protons (Mannheim & Biermann 1992). The photo-meson and photo-pair production cross sections are a factor of \(\sim 10^3\) smaller than the typical cross section of the leptonic processes requiring higher proton energies (Lorentz factors) in the range of \(10^{17} - 10^{19}\) eV (Mannheim 1993) to explain VHE emission from blazars. Also synchrotron radiation from protons has been suggested as a source of TeV photons (Mücke & Protheroe 2000; Aharonian 2000).

Strong flux variability can be used to estimate the cooling time scales and/or the acceleration time scale (whichever dominates the process) of the emission mechanism at work, providing an additional constraint to models (Maraschi et al. 1999). For example, the high energy radiation from a photo-meson or photo-pair induced cascade decays more slowly than SSC radiation (Böttcher & Dermer 1998). However, testing these models requires that the spectrum between X-rays and the TeV emission is measured on short time scales, as short as the variability time scale to better constrain the mechanism. This requires contemporaneous observations over a wide range of energies - X-rays, HE and VHE \(\gamma\)-rays - the so-called multiwavelength campaigns.
Figure 3. VHE $\gamma$-ray lightcurves of two rapid flares from Markarian 421 on May 7th and May 15th 1996 (Gaidos et al. 1996).
Figure 4. The nightly fluxes for Markarian 501 observed with the Whipple telescope are presented for the years 1995 - 1998. Figure is from Quinn et al. (1999).
Multiwavelength Observations: After the first indication for correlation of a TeV flare with an X-ray flare in 1995 (Macomb et al. 1995; Macomb et al. 1996) a series of multiwavelength campaigns involving the Whipple telescope and X-ray telescopes were initiated. In a campaign on Markarian 421, Whipple/ASCA observations between April 20 - May 5 1995 showed convincing evidence for correlations between TeV and X-ray photons (Buckley et al. 1996). These first correlated TeV/X-ray observations were undersampled and, therefore, not strictly contemporaneous. Given the short variability time scales, simultaneous observations are crucial to establish X-ray/TeV correlation. Thus, a concerted effort was undertaken by VHE telescope groups (CAT, HEGRA, and Whipple) to provide better sampling of observations.

A campaign in late April 1998 by Whipple/BeppoSAX revealed a short flare (flux halving time of 0.94 hours) at 2 TeV with a contemporaneous X-ray flare (flux halving time of 20.4 hours). The two flares are simultaneous to within 1.5 hours. These observations (Maraschi et al. 1999) provide the first evidence that the X-ray and TeV emission is well correlated on time scales of hours (Figure 5). Simultaneity of the two flares implies that the X-ray and the TeV photons arise from the same emission region, likely from the same population of synchrotron radiating electrons. This observation supports the notion that the SSC mechanism is at least partially if not dominantly at work in the γ-ray production in Markarian 421. In addition it was possible, for the first time to derive detailed energy spectra for a contemporaneous X-ray and TeV flare (Figure 6). By assuming an SSC model the spectra can be fitted yielding an accurate estimate of the physical parameters (magnetic field strength B = 0.06 G, radius of emission region R = 10^{16} cm, Doppler factor δ = 20). However, the HE-VHE part of the spectrum needs a more sensitive and wider energy coverage to tightly constrain the mechanism and rule out some of the models.

An X-ray/TeV campaign involving the Whipple, CAT and HEGRA telescopes and ASCA at X-rays shows for the first time a series of flares continuously covered (for 1 week) at X-rays (Figure 7) and good sampling at VHE energies (Takahashi et al. 1999). Again it is apparent that a better sensitivity with TeV telescopes would be required to test emission models in detail. However, observations like these indicate the good prospects for studying X-ray/TeV correlations on time scales of minutes - hours - days with multi-telescope installations located at different geographical longitude and continuous X-ray sampling to fully constrain the emission process.

Blazar multiwavelength studies including VHE γ-rays would be of limited interest if they would involve just a single source with little implications on blazars in general. The discovery of Markarian 501 as a strong γ-ray emitter peaking at TeV energies has promoted TeV blazar observations beyond the status of a fringe science. Flaring activity of Markarian 501 started in February 1997 (Protheroe, Bhat, Fleury, Lorenz 1997) lasting until October 1997 (see Catanese & Weekes 2000), inspiring numerous observations including X-ray, MeV - GeV and various TeV telescopes. Figure 8 shows the result of a multiwavelength campaign (Catanese et al. 1997; Pian et al. 1998) and the following properties are significant as to the role of TeV blazar observations:

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6 An energy range of GeV - ten's of TeV would be desirable.
Figure 5. The lightcurve of Markarian 421 during a short flare on April 21, detected by Whipple and BeppoSAX 21 from Maraschi et al. (1999). The top lightcurve shows the Whipple $\gamma$-ray rate normalized to the average rate over the observations shown. The lightcurves below are for various energy ranges of the BeppoSAX data.
Figure 6. The multiwavelength spectrum of Markarian 421 showing contemporaneous spectral data from a short flare in the X-ray and VHE regime (Maraschi et al. 1999). The solid line is a fit to the spectrum based on the SSC model. The Figure is from Maraschi et al. (1999).
Figure 7. Observations of Markarian 421 taken in 1998 April - May:
a) TeV data from CAT, HEGRA and Whipple, b) X-ray flux observed with ASCA, c) X-ray hardness ratios observed with ASCA are shown. Figure is from Takahashi et al. (1999).
Figure 8. Multiwavelength observations of Markarian 501 (Catanese et al. 1997) taken during strong flaring activity in April 1997 are shown: a) VHE $\gamma$-ray, b) hard X-ray, c) soft X-ray, d) U-band optical.
Figure 9. Multiwavelength spectrum of Markarian 501 (Catanese & Weekes 2000) from contemporaneous and archival data (Catanese et al. 1997; Catanese (1999); Kataoka et al. (1999)). The Figure is from Catanese & Weekes (2000).
1) The TeV flaring activity coincides with a strong detection by the OSSE detector aboard the CGRO between 50 - 470 keV. OSSE has detected only a few blazars (McNaron-Brown et al. 1995) whereas Markarian 501 showed the strongest flux ever detected from a blazar except for a high state from 3C273 (McNaron-Brown et al. 1997). These data suggest that there is a correlation between hard X-ray emission and TeV brightness. The hard X-ray brightness is attributed to synchrotron emission up to at least 100 keV. Therefore, in Markarian 501 the synchrotron component extends about a factor of 100 higher in energy (100 keV) than in Markarian 421 (1 keV), an unusual property even for an X-ray selected BL Lac.

2) The EGRET detector provides only an upper limit and this implies that the maximum energy output of Markarian 501 peaks in the TeV and not in the GeV regime (see multiwavelength spectrum in Figure 9). It is interesting to note that observations of Markarian 501 taken in 1996 by Kataoka et al. (1999) show a synchrotron peak at \( \sim 2\) keV. This implies that the synchrotron peak of Markarian 501 shifts to higher energies when flaring (Figure 9).

The fact that Markarian 501 was discovered as a \( \gamma \)-ray source by a TeV telescope (Quinn et al. 1996) (and was not an EGRET source at that time) suggests, that besides blazars peaking in radio and at EGRET energies, also referred to as radio selected BL Lacs, the existence of a class of extreme blazars, radiating most powerfully between 50 GeV to TeV energies (Ghisellini 1999). Also Markarian 421 supports this theme since it is one of the weakest nearby EGRET blazars, yet it is detected at TeV energies. Ghisellini (1999) suggests that even a class of more extreme BL Lacs can exist, with the synchrotron emission peak at MeV energies and the inverse Compton peaking at multi-TeV energies.

**VHE \( \gamma \)-ray Spectra:** As mentioned in the previous section, the understanding of the emission process at work requires the measurement of the energy spectrum over a wide range of energies. Ideally one would like to accomplish complete coverage between X-rays to VHE \( \gamma \)-rays. Furthermore, due to the extreme variability of blazars at all wavelengths it is crucial to derive accurate contemporaneous X-ray - VHE spectra with dense temporal coverage. In this section I want to emphasize the progress that has been made with existing Cherenkov telescopes to achieve this difficult task.

Energy spectra for Markarian 421 and Markarian 501 have been derived by various Cherenkov telescope groups. Strong flaring activity as observed from Markarian 421 in May 1996 (Gaidos et al. 1996) has resulted in the first statistically accurate energy spectrum between 560 GeV - 5 TeV (Zweerink et al. 1997) showing no evidence for a cutoff (also supported by large zenith angle observations (Krennrich et al. 1997)). The averaged spectrum of Markarian 501 during the flaring activity in 1997 is shown in Figure 10 (Samuelson et al. 1998) as measured by the Whipple collaboration. The spectrum between 260 GeV - 12 TeV is clearly curved and can be well fitted with a parabolic spectrum:

\[
J(E) \propto E^{-2.22 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}} - (0.47 \pm 0.07) \log_{10}(E) \text{ photons m}^{-2}\text{s}^{-1}\text{TeV}^{-1}.
\]

\(^7\)The accuracy of spectral indices should be better than \( \pm 0.1 \) to distinguish emission models.
The energy spectrum of Markarian 501 has been derived by several groups confirming the curvature in the spectrum (Aharonian et al. 1999b; Djannati-Atai et al. 1999; Aharonian et al. 2000b) and showing good agreement between the various groups. Furthermore, Aharonian et al. (1999b, 2000b) were able to extend the spectrum in energy up to 24 TeV. They conclude that a cutoff in the source spectrum below 16.5 TeV can be excluded (Aharonian et al. 2000b). This result by itself has major implications for the extragalactic IR background density. Limits to the extragalactic IR density have been derived by several authors (Stanev & Franceschini 1998; Biller et al. 1998; Vassiliev 2000; Primack et al. 1999), showing that at some wavelengths the VHE limits are a factor of 50 below limits from direct IR measurements. More extensive discussions of the subject can be found elsewhere (Stanev & Franceschini 1998; Biller et al. 1998; Vassiliev 2000; Primack, Bullock, Somerville & MacMinn 1999; Catanese & Weekes 2000; Stecker 2000; Protheroe & Mayer 2000).

Energy spectra of comparable statistical accuracy have been derived for Markarian 421 (Krennrich et al. 1999a) by combining data sets from various
Figure 11. The energy spectrum of Markarian 501 (filled circles) between 260 GeV - 12 TeV compared with the spectrum of Markarian 421 (stars) (Krennrich et al. 1999).
strong flares (1-10 Crab) in 1995 and 1996. Figure 11 shows the energy spectrum of Markarian 421 and Markarian 501 together in one plot. The resulting spectrum for Markarian 421 is well fitted by a simple power law:

$$J(E) \propto E^{-2.54 \pm 0.03_{\text{stat}} \pm 0.10_{\text{syst}}} \text{photons m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$$

This is different from the Markarian 501 spectrum, which cannot be fitted by simple power law, requiring a curved fit. The spectra of Markarian 501 and Markarian 421 are different and because the two blazars have almost the same redshift, the differences in their spectra must be intrinsic to the sources (or absorption near the source) and not due to interaction with the extragalactic IR background. The observed difference could be related to the fact that for Markarian 501, because the synchrotron and inverse Compton peaks are shifted to higher energies in comparison to Markarian 421, the detected $\gamma$-rays are closer to the peak. At the peak one would naturally expect more curvature than further beyond the peak (Krennrich et al. 1999a; Djannati-Atai et al. 1999).

Observation of Markarian 421 by Aharonian et al. (1999c) in 1997 and 1998 reveals a different spectrum, showing a differential spectral index of $3.09 \pm 0.07 \pm 0.10$, but again with no evidence for curvature. It should be emphasized that the flux levels during these observations (1997, 1998) were only $\sim 0.5$ Crab, substantially below the flux levels of the Whipple observations in 1995 - 1996 (1-10 Crab). This might indicate that the energy spectrum of Markarian 421 becomes harder with increasing flux during flaring activity. Further observations are necessary to resolve this question.

Measurements of spectral variability hold great promise to deliver an additional constraint for emission models and is therefore an important goal for VHE observations with future instruments. Evidence for variability in the spectrum of Markarian 501 has been reported by Piron et al. (1999), indicating spectral softening during a period of lower emission in 1998. This result supports the picture that also the inverse Compton peak shifts to lower energies as the flux decreases. This concurs well with the notion by Kataoka et al. (1999) showing that the synchrotron peak (X-rays) was at much lower energy ($\sim 2$ keV) during a period of low emission.

Energy spectra are key to the understanding of the emission processes at work in all $\gamma$-ray sources and will continue to take an important role for strong detections with future generation instruments.

$1ES2344+514$, $1ES1959+650$, $1ES2155-304$, $3C66$: The possibility of several more blazars detected at TeV energies is an intriguing one. The most severe limits to IR background models could be derived if the observation of 3C66 (Neshpor et al. 1998) were confirmed. For details on the other sources see Catanese & Weekes (2000) and references therein. All of these sources need confirmation.

3. Next Generation Detectors

Existing atmospheric Cherenkov detectors (see: Ong 1998; Catanese & Weekes 2000) come in a variety of designs. The instruments fall into two categories: imaging and wavefront sampling detectors. Imaging telescopes (Weekes et al. 1989) record an image of the Cherenkov light of an air shower and use the image’s
shape, orientation and angular position to derive the arrival direction, primary energy and type of primary particle ($\gamma$-ray, cosmic-ray nucleon or muon). Wavefront sampling with heliostats relies on the Cherenkov light detection at various locations of the Cherenkov light pool using the light intensity and relative arrival times to recognize the arrival direction, primary energy and type of primary particle (Ong et al. 1996; Pare et al. 1996). Imaging telescopes have an excellent sensitivity, wavefront sampling detectors could potentially reach the lowest energy threshold of any ground-based instrument.

The success of the present generation imaging telescopes (CANGAROO, CAT, HEGRA, Whipple) has established a good sensitivity of the atmospheric imaging technique, and it has also become apparent that the technique can be substantially improved and the energy range extended to lower energies. A third generation of imaging detectors is currently under construction. The MAGIC telescope project consists of a single 17 m optical reflector which is likely to reach an energy threshold of 30 GeV using standard photomultipliers and 15 GeV if equipped with photodetectors containing GaAsP photocathodes (Barrio et al. 1998). The other projects, CANGAROO III (Mori et al. 1999), HESS (Hofmann et al. 1999) and VERITAS (Weekes et al. 1999; Krennrich et al. 1999b) are based on stereoscopic imaging. The idea of the stereo concept with multiple instruments has been first demonstrated by Grindlay (1972). Its realization with modern state-to-the-art telescopes has been achieved by Daum et al. (1997) using the HEGRA telescope array (4 telescope of 8.5 m$^2$ mirror area each) showing excellent angular resolution and background rejection at 1 TeV (Konopelko et al. 1999).

Detailed descriptions of the various instruments are given elsewhere (e.g., see “GeV-TeV Gamma Ray Astrophysics Workshop” (1999)). Their major properties and their impact on the various science topics are summarized (+ + for very important; + important; o for less important) in table 2. The most relevant improvements of the next generation of telescopes can be briefly summarized as follows:

- Better flux sensitivity: the arrays of IACTs such as CANGAROO, HESS & VERITAS are expected to reach flux sensitivities 10 - 20 times better than any previous installation (Weekes et al. 1999).
- Reduced energy threshold: most new instruments will have energy thresholds significantly below 100 GeV, MAGIC will have the lowest threshold of 30 GeV.
- Energy resolution: for spectroscopic measurements the resolution will be substantially improved through stereoscopic observations and improved calibration techniques. An energy resolution of up to 10-15% can be achieved over two decades in energy.
- Angular resolution: a resolution of better than 0.1° at E > 100 GeV (0.03° at 1 TeV) for individual photons can be reached. A source location capability of 0.005° will be possible for strong sources.
- Larger effective area of > 0.1 km$^2$ is possible to allow measurements of short flux variability.
Table 2. Instrument requirements for future VHE telescopes

| Instruments: | monitoring capability | low energy | high energy | field of view | energy resol. | angular resol. σ_θ @200 GeV | @100 GeV |
|--------------|-----------------------|------------|-------------|---------------|---------------|-----------------|---------|
| CANGAROO III | 1 - 4                 | 100        | >10         | 3 - 8         | NA            | NA              | NA      |
| MAGIC        | 1                     | 30         | >10         | 3             | 20%           | 0.2°            |         |
| HESS         | 1 - 4                 | 40         | >10         | 3 - 8         | 15%           | 0.1°            |         |
| VERITAS      | 1 - 7                 | 50         | >10         | 3 - 10        | 15%           | 0.09°           |         |
| Science:     |                       |            |             |               |               |                 |         |
| Plerions     | o                     | +          | ++          | o             | ++            | +               |         |
| Pulsars      | o                     | ++         | o           | o             | ++            | o               |         |
| Shell-type SNRs | o               | +          | ++          | ++            | ++            | ++              |         |
| EGRET        |                       |            |             |               |               |                 |         |
| Unidentified | o                     | ++         | +           | ++            | ++            | ++              | ++      |
| Gal. Diffuse | o                     | ++         | +           | ++            | ++            | +               |         |
| Gal. Plane Survey | o               | ++         | o           | ++            | +             | ++              | ++      |
| Blazars z < 0.1 | ++               | +          | ++          | o             | ++            | o               |         |
| Blazars z > 0.1 | ++               | ++         | +           | o             | ++            | o               |         |
| Gamma Ray    |                       |            |             |               |               |                 |         |
| Bursts       | ++                    | ++         | +           | o             | ++            | +               |         |
| Extragalactic IR |                |            |             |               |               |                 |         |
| Background   |                       |            |             |               |               |                 |         |
| Supersymmetric particle decay | o          | ++         | o           | +             | ++            | +               |         |
The scientific potential for the various science topics can be summarized as follows:

**Plerions:** A VERITAS-like detector with a flux sensitivity of 0.5% of the Crab should be capable of detecting Crab-like plerions out to a distance of 20 kpc (see Weekes et al. 1999). This will allow a search for synchrotron self-Compton dominated plerions (Crab-like) over 2/3 of our galaxy.

**Pulsars:** Because of the potentially sharp cutoff in pulsar energy spectra an energy threshold of $<50$ GeV is desirable. The excellent sensitivity due to a large collection area and excellent energy resolution of the next generation imaging telescopes holds great promise in resolving the question as to where $\gamma$-rays in pulsars originate.

**Shell-type SNRs:** Next generation telescope arrays with their arc-minute angular resolution will be capable of mapping the sites of putative cosmic-ray acceleration and correlate them with interstellar matter density and compare them with their X-ray luminosity. The versatility of telescope arrays allows a wide-field-of-view mode for the study of more extended SNRs. The good energy resolution of arrays will help to measure the energy spectrum from 50 GeV to 10 TeV. Ultimately a combined spectrum including data from GLAST and VHE telescopes will be a powerful tool to separate $\gamma$-ray emission of IC origin from nucleonic origin.

**Galactic diffuse emission:** The intrinsically large collection area of ground-based telescope combined with a low energy threshold and a good energy resolution should allow the measurement of the energy spectrum of the galactic diffuse emission from different regions in the galaxy in the range of 50 GeV - TeV. Arrays of Cherenkov telescopes increase the field-of-view by the use of sub-arrays (e.g., VERITAS: two arrays of 3 telescopes).

**Blazars:** Ground-based Cherenkov telescopes have the highest sensitivity to short $\gamma$-ray flares from blazars because of their large collection areas. Thus, detailed multiwavelength studies on scales of minutes to hours is the domain of the X-ray and ground-based VHE instruments. Maybe most important will be multiwavelength studies that include the whole $\gamma$-ray spectrum from MeV energies to ten’s of TeV and a dense sampling involving GLAST together with a number of Cherenkov telescopes at different geographical longitude. It is important to realize that observations with the next generation space telescope GLAST covering 20 MeV - 300 GeV together with ground-based telescopes (e.g., VERITAS: 50 GeV-50 TeV) will provide for the first time a significant overlap in energy. A cross-calibration between the ground-based and satellite telescopes will allow the derivation of detailed energy spectra over 6 orders of magnitude in energy.

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