The Status and future of ground-based TeV gamma-ray astronomy
Reports of Individual Working Groups

1 Extragalactic VHE Astrophysics

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1.1 Introduction

A next-generation gamma-ray experiment will make extragalactic discoveries of profound importance. Topics to which gamma-ray observations can make unique contributions are the following: (i) the environment and growth of Supermassive Black Holes; (ii) the acceleration of cosmic rays in other galaxies; (iii) the largest particle accelerators in the Universe, including radio galaxies, galaxy clusters, and large scale structure formation shocks; (iv) study of the integrated electromagnetic luminosity of the Universe and intergalactic magnetic field strengths through processes including pair creation of TeV gamma rays interacting with infrared photons from the Extragalactic Background Light (EBL).

The following sections will describe the science opportunities in these four areas. Gamma-ray bursts and extragalactic searches for dark matter annihilation gamma rays are discussed in separate sections.

1.2 Gamma-ray observations of supermassive black holes

Supermassive black holes (SMBH) have masses between a million and several billion solar masses and exist at the centers of galaxies. Some SMBHs, called Active Galactic Nuclei (AGN) are strong emitters of electromagnetic radiation. Observations with the *EGRET Energetic Gamma-Ray Experiment Telescope* on board of the Compton Gamma-Ray Observatory (CGRO) revealed that a certain class of AGN known as blazars are powerful and variable emitters, not just at radio through optical wavelengths, but also at ≥100 MeV gamma-ray energies [5]. EGRET largely detected quasars, the most powerful blazars in the Universe. Observations with ground-based Cherenkov telescopes showed that blazars emit even at TeV energies [6]. In the meantime, more than twenty blazars have now been identified as sources of >200 GeV gamma rays with redshifts ranging from 0.031 (Mrk 421) [6] to 0.536 (3C 279) [69] [1]. Most TeV bright sources are BL Lac type objects, the low power counterparts of the quasars detected by EGRET. The MeV to TeV gamma-ray emission from blazars is commonly thought to originate from highly relativistic collimated outflows (jets) from mass accreting SMBHs that point at the observer [3, 4]. The only gamma-ray emitting AGN detected to date that are not blazars are the radio galaxies Centaurus A [1] and M87 [2]. The observation of blazars in the gamma-ray band has had a major impact on our understanding of these sources. The observation

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[1] Up-to-date lists of TeV γ-ray sources can be found at the web-sites: http: //tevcat.uchicago.edu and http: //www.mpp.mpg.de/ ∼rwagner/sources/.

of rapid flux variability on time scales of minutes together with high gamma-ray and optical fluxes [11, 63] implies that the accreting black hole gives rise to an extremely relativistic jet-outflow with a bulk Lorentz factor exceeding 10, most likely even in the range between 10 and 50 [64, 65]. Gamma-ray observations thus enable us to study plasma which moves with $\geq$99.98% of the speed of light. Simultaneous broadband multiwavelength observations of blazars have revealed a pronounced correlation of the X-ray and TeV gamma-ray fluxes [12, 13, 16, 24]. The X-ray/TeV flux correlation (see Fig. 1) suggests that the emitting particles are electrons radiating synchrotron emission in the radio to X-ray band and inverse Compton emission in the gamma-ray band.

Blazars are expected to be the most copious extragalactic sources detected by ground-based IACT arrays like VERITAS and by the satellite borne gamma-ray telescope Fermi. For extremely strong sources, IACT arrays will be able to track GeV/TeV fluxes on time scales of seconds and GeV/TeV energy spectra on time scales of a few minutes. Resolving the spectral variability during individual strong flares in the X-ray and gamma-ray bands should lead to the unambiguous identification of the emission mechanism. The present generation of IACTs will be able to track spectral variations only for a very small number of sources and only during extreme flares. The next-generation gamma-ray experiments will be able to do such studies for a large number of sources on a routine basis. Sampling the temporal variation of broadband energy spectra from a few tens of GeV to several TeV will allow us to use blazars as precision laboratories to study particle acceleration and turbulence in astrophysical plasmas, and to determine the physical parameters describing a range of different AGN. The observations of blazars hold the promise to reveal details about the inner workings of AGN jets. Obtaining realistic estimates of the power in the jet, and the jet medium will furthermore constrain the origin of the jet and the nature of the accretion flow.

Recently, spectracular results have been obtained by combining monitoring VLBA, X-ray and TeV γ-ray observations. This combination has the potential to pinpoint the origin of the high energy emission based on the high resolution radio images, and thus to directly confirm or to refute models of jet formation. For example, radio VLBA, optical polarimetry, X-ray and TeV γ-ray observations of the source BL Lac seem to indicate that a plasma blob first detected with the VLBA subsequently produces an X-ray, an optical and a γ-ray flare [67]. A swing of the optical polarization seems to bolster the case for a helical magnetic field as predicted by magnetic models of jet formation and acceleration. Presently such observations are extremely difficult as the current instruments can detect sources like M 87, BL Lac, W Com only in long observations or during extreme flares. Next-generation γ-ray instruments will allow us to study the correlation of fast TeV flares and radio features on a routine basis.

In addition to ground-based radio to optical coverage, several new opportunities might open up within the next decade. The Space Interferometry Mission (SIM) will be able to image emerging plasma blobs with sub milli-arcsec angular resolution [14]. The center may be located with an accuracy of a few micro-arcsec. For a nearby blazar at z=0.03, 1 milli-arcsec corresponds to a projected distance of 0.6 pc. The SIM observations could thus image the blobs that give rise to the flares detected in the gamma-ray regime. Joint X-ray/radio interferometry observations already give some tentative evidence for the emergence of radio blobs correlated with X-ray flares. If a Black Hole Finder Probe like the Energetic X-ray Imaging Space Telescope (EXIST) [15] will be launched, it would provide reliable all-sky, broad-bandwidth (0.5-600 keV), and high-sensitivity X-ray coverage for all blazars in the sky. EXIST's full-sky sensitivity would be 2×10^{-12} ergs cm^{-2} s^{-1} for 1 month of integration. For bright sources, EXIST could measure not only flux variations but also the polarization of hard X-rays. Opportunities arising from neutrino coverage will be described below.

At the time of writing this white paper, the Fermi gamma-ray telescope is in the process of

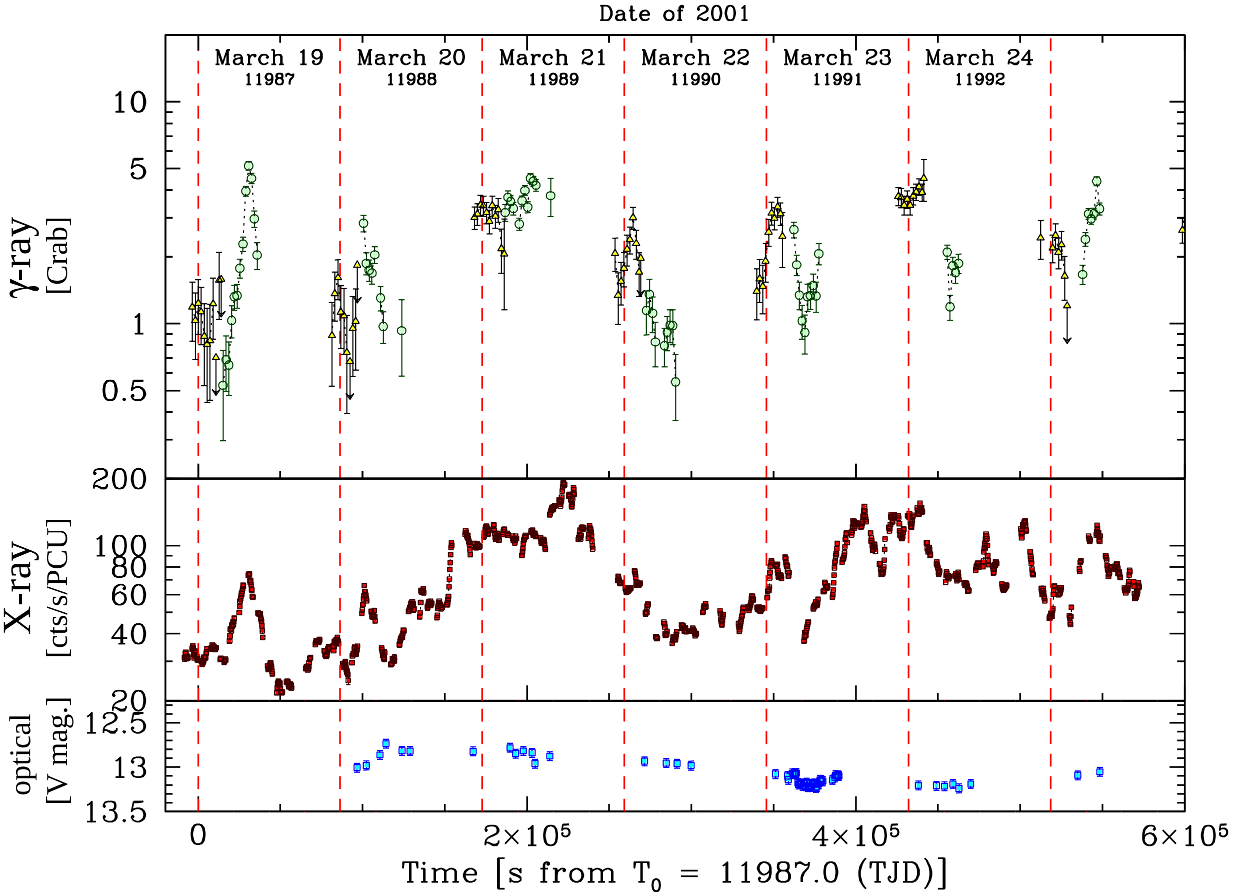

Figure 1: Results from 2001 Rossi X-ray Timing Explorer (RXTE) 2-4 keV X-ray and Whipple (full symbols) and HEGRA (open symbols) gamma-ray observations of Mrk 421 in the year 2001 [24]. The X-ray/gamma-ray fluxes seem to be correlated. However, the interpretation of the data is hampered by the sparse coverage at TeV gamma rays.

detecting a few thousand blazars. The source sample will make it possible to study the redshift dependent luminosity function of blazars, although the identification of sources with optical counterparts may be difficult for the weaker sources of the sample, owing to Fermi's limited angular resolution. Another important task for the next-generation instrument will be to improve on the Fermi localization accuracies, and thus to identify a large number of the weaker Fermi sources.

Independent constraints on the jet power, kinematics, and emission processes can be derived from GeV-TeV observations of the large scale (up to hundreds of kpc) jets recently detected by Chandra. Although such large scale jets will not be spatially resolved, the fact that the gamma-ray emission from the quasar core is highly variable permits us to set upper limits to the steady GeV-TeV large scale jet emission [17]. In the case of the relatively nearby 3C 273, for example, the electrons that produce the large scale jet IR emission will also produce a flat GeV component. The fact that this emission is weaker than the EGRET upper limit constrains the Doppler factor of the large scale jets to less than 12, a value that can be pushed down to 5 with Fermi observations. Such low values of delta have implications on the nature of the large scale jet X-ray emission observed by Chandra. In particular, they disfavor models in which the X-ray emission is inverse Compton scattering of the cosmic microwave background (CMB), because the jet power required increases beyond the so-called Eddington luminosity, thought by many to be the maximum luminosity that can be channeled continuously in a jet. A synchrotron interpretation for the X-ray emission, requiring significantly less jet power, postulates a population of multi-TeV electrons that will unavoidably up-scatter the CMB to TeV energies. The existing 3C 273 shallow HESS upper limit constrains the synchrotron interpretation to Doppler factors less than 10. Combining deep TeV observations with a next-generation experiment with Fermi observations holds the promise of confirming or refuting the synchrotron interpretation and constraining the jet power.

Whereas the X-ray/gamma-ray correlation favors leptonic models with electrons as the emitters of the observed gamma-ray emission, hadronic models are not ruled out. In the latter case, the high-energy component is synchrotron emission, either from extremely high-energy (EHE) protons [31, 32, 33], or from secondary e^+/e^- resulting from synchrotron and pair-creation cascades initiated by EHE protons [34] or high-energy electrons or photons [35, 36, 37, 38]. If blazars indeed accelerate UHE protons, it might even be possible to correlate their TeV gamma-ray emission with their flux of high-energy neutrinos detected by the IceCube detector [39]. The high sensitivity of a next-generation ground-based experiment would be ideally suited to perform such multi-messenger studies.

Although most observations can be explained with the emission of high-energy particles that are accelerated in the jets of AGN , the observations do not exclude that the emitting particles are accelerated closer to the black hole. If the magnetic field in the black hole magnetosphere has a poloidal net component on the order of $B_{100} = 100$ G, both the spinning black hole [19] and the accretion disk [20, 18] will produce strong electric fields that could accelerate particles to energies of $2 \times 10^{19}\ B_{100}$ eV. High-energy protons could emit TeV photons as curvature radiation [21], and high-energy electrons as Inverse Compton emission [22]. Such models could be vindicated by the detection of energy spectra, which are inconsistent with originating from shock accelerated particles. An example for the latter would be very hard energy spectra which require high minimum Lorentz factors of accelerated particles.

The improved data from next-generation gamma-ray experiments can be compared with improved numerical results. The latter have recently made very substantial progress. General Relativistic Magnetohydrodyamic codes are now able to test magnetic models of jet formation and acceleration (see the review by [68]). The Relativistic-Particle-in-Cell technique opens up the possibility of greatly improving our understanding a wide range of issues including jet bulk acceleration, electromagnetic energy transport in jets, and particle acceleration in shocks and in magnetic reconnection while incorporating the different radiation processes [27, 28, 29, 30].

Blazar observations would benefit from an increased sensitivity in the 100 GeV to 10 TeV energy range to discover weaker sources and to sample the energy spectra of strong sources on short time scales. A low energy threshold in the 10-40 GeV range would be beneficial to avoid the effect of intergalactic absorption that will be described further below. Increased sensitivity at high energies would be useful for measuring the energy spectra of a few nearby sources like M 87, Mrk 421, and Mrk 501 at energies $\gg$10 TeV and to constrain the effect of intergalactic absorption in the wavelength range above 10 microns. The interpretation of blazar data would benefit from dense temporal sampling of the light curves. Such sampling could be achieved with gamma-ray experiments located at different longitudes around the globe.

1.3 Cosmic rays from star-forming galaxies

More than 60% of the photons detected by EGRET during its lifetime were produced as a result of interactions between cosmic rays (CRs) and galactic interstellar gas and dust. This diffuse radiation represents approximately 90% of the MeV-GeV gamma-ray luminosity of the

Milky Way [40]. Recently H.E.S.S. reported the detection of diffuse radiation at TeV energies from the region of dense molecular clouds in the innermost 200 pc around the Galactic Center [41], confirming the theoretical expectation that hadronic CRs could produce VHE radiation in their interaction with atomic or molecular targets, through the secondary decay of π°'s. Only one extragalactic source of diffuse GeV radiation was found by EGRET: the Large Magellanic Cloud, located at the distance of ~ 55 kpc [42]. A simple re-scaling argument suggests that a putative galaxy with Milky-Way-like gamma-ray luminosity, located at the distance of 1 Mpc, would have a flux of approximately 2.5×10^{-8} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (> 100MeV), well below the detection limit of EGRET and $\sim 2\times10^{-4}$ of the Crab Nebula flux (> 1 TeV), well below the sensitivity of VERITAS and H.E.S.S. Thus, a next-generation gamma-ray observatory with sensitivity at least an order of magnitude better than VERITAS would allow the mapping of GeV-PeV cosmic rays in normal local group galaxies, such as M31, and study diffuse radiation from more distant extragalactic objects if their gamma-ray luminosity is enhanced by a factor of ten or more over that of the Milky Way.

Nearby starburst galaxies (SBG's), such as NGC253, M82, IC342, M51 exhibit regions of strongly enhanced star formation and supernova (SN) explosions, associated with gas clouds which are a factor of $10^2 - 10^5$ more dense than the average Milky Way gas density of ~ 1 proton per cm^3. This creates nearly ideal conditions for the emission of intense, diffuse VHE radiation, assuming that efficient hadronic CR production takes place in the sites of the SNR's (i.e. that the galactic CR origin paradigm is valid) and in colliding OB stellar winds [43]. In addition, leptonic gamma-ray production through inverse-Compton scattering of high density photons produced by OB associations may become effective in star forming regions [44]. Multiple attempts to detect SBGs have been undertaken by the first generation ground-based gamma-ray observatories. At TeV energies, M82, IC342, M81, and NGC3079 were observed by the Whipple 10 m telescope [45], while M82 and NGC253 were observed by HEGRA. However, none of these objects were detected. A controversial detection of NGC 253 by the CANGAROO collaboration in 2002 [46] was ruled out by H.E.S.S. observations [47]. The theoretical predictions of TeV radiation from starburst galaxies have not yet been confirmed by observations and these objects will be intensively studied by the current generation instruments during the next several years. The optimistic theoretical considerations suggest that a few SBG's located at distances less than ~ 10 Mpc may be discovered. Should this prediction be confirmed, a next-generation gamma-ray observatory with sensitivity at least an order of magnitude better than VERITAS will potentially discover thousands of such objects within the ~ 100 Mpc visibility range. This will enable the use of SBG's as laboratories for the detailed study of the SNR CR acceleration paradigm and VHE phenomena associated with star formation, including quenching effects due to evacuation of the gas from star forming regions by SNR shocks and UV pressure from OB stars.

If accelerated CR's are confined in the regions of high gas or photon density long enough that the escape time due to diffusion through the magnetic field exceeds the interaction time, then the diffuse gamma-ray flux cannot be further enhanced by an increased density of target material, and instead an increased SN rate is needed. Ultra Luminous InfraRed Galaxies (ULIRGs), which have SN rates on the scale of a few per year (compared to the Milky Way rate of ~ 1 per century) and which also have very large amounts of molecular material, are candidates for VHE emission [48]. Although located at distances between ten and a hundred times farther than the most promising SBG's, the ULIRG's Arp220, IRAS17208, and NGC6240 may be within the range of being detected by Fermi, VERITAS and H.E.S.S. [49]. Next-generation gamma-ray instruments might be able to detect the most luminous objects of this type even if they are located at ~ 1 Gpc distances. Initial studies of the population of ULIRGs indicate that these objects underwent significant evolution through the history of the Universe and that at the moderate redshift

($z < 1$) the abundance of ULIRGs increases. Any estimate of the number of ULIRGs that may be detected is subject to large uncertainties due to both the unknown typical gamma-ray luminosity of these objects and their luminosity evolution. However, if theoretical predictions for Arp220 are representative for objects of this type, then simple extrapolation suggests $> 10^2$ may be detectable.

The scientific drivers to study ULIRG's are similar to those of SBGs and may include research of galaxy gamma-ray emissivity as a function of target gas density, supernova rate, confining magnetic field, etc. In addition, research of ULIRGs may offer a unique possibility to observe VHE characteristics of star formation in the context of the recent history of the Universe ($z < 1$) since ULIRGs might be detectable to much further distances. Other, more speculative, avenues of research may also be available. A growing amount of evidence suggests that AGN feedback mechanism connects episodes of intense starbursts in the galaxies with the accretion activity of central black holes. One can wonder then if a new insight into this phenomena can be offered by observation of VHE counterparts of these processes detected from dozens of ULIRGs in the range from 0.1-1 Gpc.

1.4 The largest particle accelerators in the Universe: radio galaxies, galaxy clusters, and large scale structure formation shocks

The possibility of observing diffuse GeV and TeV radiation from even more distant, rich galaxy clusters (GCs) has widely been discussed in the literature. As the Universe evolves, and structure forms on increasingly larger scales, the gravitational energy of matter is converted into random kinetic energy of cosmic gas. In galaxy clusters, collisionless structure formation shocks, triggered by accretion of matter or mergers, are thought to be the main agents responsible for heating the inter-cluster medium (ICM) to temperatures of ~ 10 keV. Through these processes a fraction of gravitational energy is converted into the kinetic energy of non-thermal particles: protons and electrons. Galactic winds [50] and re-acceleration of mildly relativistic particles injected into the ICM by powerful cluster members [51] may accelerate additional particles to non-thermal energies. Cosmic ray protons can escape clusters diffusively only on time scales much longer than the Hubble time. Therefore, they accumulate over the entire formation history [50] and interact with the intercluster thermal plasma to produce VHE gamma radiation. Theoretical predictions for the detection of such systems in gamma rays by VERITAS and H.E.S.S. include clusters in the range from $z = 0.01$ to $z = 0.25$ (see Fig. 2) [43, 52, 53]. Objects of this category were observed with Whipple [54] and H.E.S.S. [55] but were not detected. Multiple attempts to find gamma-ray signals from GCs in EGRET data also failed. Nevertheless, a large theoretical interest [56, 57, 58] motivates further observations of the particularly promising candidates, such as the Coma and Perseus clusters by VERITAS and H.E.S.S.. If nearby representatives of the GC class are detected, a next-generation gamma-ray observatory with sensitivity increased by a factor of 10 would be able to obtain spatially resolved energy spectra from the close, high-mass systems, and should be able to obtain flux estimates and energy spectra of several dozen additional clusters. The detection of gamma-ray emission from galaxy clusters would make it possible to study acceleration mechanisms on large scales (> 10 kpc). It would permit measurement of the energy density of non-thermal particles and investigation of whether they affect the process of star formation in GCs, since their equation of state and cooling behavior differs from that of the thermal medium. If cosmic ray protons indeed contribute noticeably to the pressure of the ICM, measurements of their energy density would allow for improved estimates of the cluster mass based on X-ray data, and thus improve estimates of the universal baryon fraction. Based on population studies of the gamma-ray fluxes from GCs, one could explore the correlation of gamma-ray luminosity and spectrum with cluster mass, temperature, and redshift. If such correlations are found, one could imagine using GCs as steady "stan-

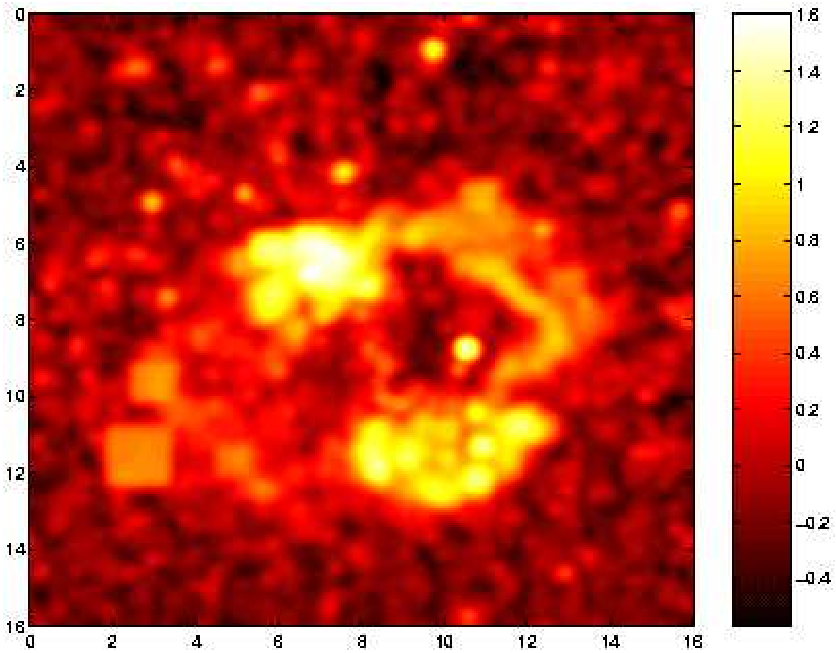

Figure 2: Results from a cosmological simulation showing how the > 10 GeV gamma-ray emission from a nearby rhich galaxy cluster could look like when mapped with a gamma-ray telescope with 0.2° angular resolution. The image covers a 16° × 16° region (color scale: $\log(J/\bar{J})$ for an average >10 GeV flux of $\bar{J} = 8.2\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1}) (from [52])

dard candles" to measure the diffuse infrared and visible radiation of the Universe through pair-production attenuation of gamma rays. From a theoretical point of view the spectral properties of gamma-ray fluxes from GCs might be better understood than the intrinsic properties of blazars.

The anticipated discovery of extragalactic sources by VERITAS and H.E.S.S. will put theoretical predictions discussed here on firmer ground, at least for the number of sources that the next generation ground-based observatory may detect. Over the next five years, Fermi will make major contributions to this area of studies. If the origin of gamma radiation in these sources is hadronic, Fermi should be able to detect most of the SBGs, ULIRGs, and GCs, which could potentially be detected by VERITAS and H.E.S.S. Under some scenarios, in which gamma rays are produced via leptonic mechanisms, a fraction of sources may escape Fermi detection (M82 might be such example), yet may still be detectable with VERITAS and H.E.S.S. Future theoretical effort will be required to guide observations of these objects. In general, benefiting from the full sky coverage of Fermi, a program to identify the Fermi sources using the narrow field of view ACT observatories of the present day will be possible, and it is likely that diffuse gamma-ray extragalactic sources will be discovered. Fermi will measure the galactic and extragalactic gamma-ray backgrounds with unprecedented accuracy and will likely resolve the main contributing populations of sources in the energy domain below a few GeV. The task of determining the contribution from the diffuse gamma-ray sources to the extragalactic background in the range above a few GeV to ~ 100 GeV will be best accomplished by the next generation ground-based instrument, capable of detecting a large number of sources rather than a few. Most of these sources are anticipated to be weak, so they will require deep observations.

Large scale structure formation shocks could accelerate protons and high-energy electrons out of the intergalactic plasma. Especially in the relatively strong shocks expected on the outskirts of clusters and on the perimeters of filaments, PeV electrons may be accelerated in substantial numbers. CMB photons Compton scattered by electrons of those energies extend into the TeV gamma-ray spectrum. The energy carried by the scattered photons cools the electrons rapidly enough that their range is limited to regions close to the accelerating shocks. However, simulations have predicted that the flux of TeV gamma rays from these shocks can be close to detection limits by the current generation of ground-based gamma-ray telescopes [59]. If true, this will be one of the very few ways in which these shocks can be identified, since very low thermal gas densities make their X-ray detection virtually impossible. Since, despite the low gas densities involved, these shocks are thought to be a dominant means of heating cluster gas, their study is vital to testing current models of cosmic structure formation.

The origin of ultra-high-energy cosmic rays (UHECRs, $E \gtrsim 10^{16}\,\mathrm{eV}$) is one of the major unsolved problems in contemporary astrophysics. Recently, the Auger collaboration reported tentative evidence for a correlation of the arrival directions of UHECRs with the positions of nearby Active Galactic Nuclei. Gamma-ray observations may be ideally suited to study the acceleration process, as the UHECRs must produce gamma rays through various processes. The UHECRs may be accelerated far away from the black hole where the kpc jet is slowed down and dissipates energy. If they are accelerated very close to the black hole at ∼pc distances, the high-energy particle beam is expected to convert into a neutron beam through photo-hadronic interactions [62]. On a length scale $l \sim 100\,(E_n/10^{19}\,\mathrm{eV})\,\mathrm{kpc}$ the neutron beam would convert back into a proton beam through beta decays.

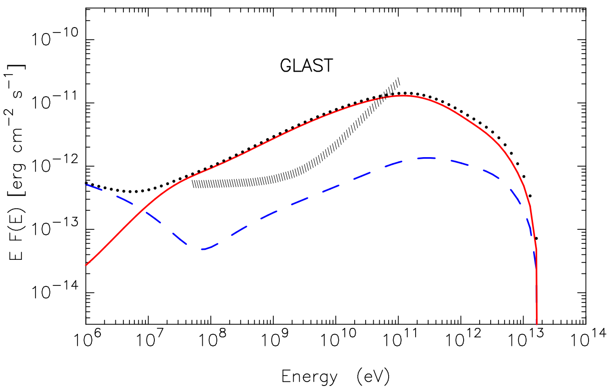

Figure 3: Fluxes from the electromagnetic cascade initiated in Cyg A by UHECRs assuming the total injection power of secondary UHE electrons and gamma rays injected at $\leq 1\,\mathrm{Mpc}$ distances about 10^{45} erg/s. The solid and dashed lines show the synchrotron and Compton fluxes, respectively.

The interaction of UHECR with photons from the Cosmic Microwave Background (CMB) creates secondary gamma rays and electrons/positrons. Depending on the strength of the intergalactic magnetic field (B_{IGMF}), a next-generation ground-based gamma-ray experiment could detect GeV/TeV gamma rays from synchrotron emission of first generation electrons/positrons ($B_{\mathrm{IGMF}} \geq 10^{-9}$ G), or inverse Compton radiation from an electromagnetic cascade ($B_{\mathrm{IGMF}} \leq 10^{-9}$ G) [61]. Figure 3 shows gamma-ray fluxes expected from the electromagnetic cascade initiated in the CMBR and $B = 3\,\mu G$ environment of Cyg A by injecting 10^{45} erg/s of secondary electrons and/or gamma rays from GZK protons. For the distance to Cyg A of $\simeq 240\,\mathrm{Mpc}$ the assumed radial size of the cluster $R <\sim 1\,Mpc$ corresponds to an extended source, or halo, of angular size <∼ 14 arcmin. Although the absorption in EBL at TeV energy is significant, the source should be detectable with a next-generation experiment because the source spectrum is very hard owing to synchrotron emission of UHE electrons. The detection of such emission could give information about the ≫TeV luminosity of these sources, about the intensity and spectrum of the EBL, and about the strength of the IGMF. A few aspects will be discussed further below.

A next-generation experiment might also be able to detect gamma-ray haloes with diameters of a few Mpc around superclusters of galaxies. Such haloes could be powered by all the sources in the supercluster that accelerate UHECRs. The size of the halo in these cases will be defined by the combination of gyroradius of the UHE electrons and their cooling path (synchrotron and Compton in Klein-Nishina regime). The spectral and spatial distibutions of such halos will contain crucial information about the EBL and intergalactic magnetic fields.

1.5 Extragalactic radiation fields and extragalactic magnetic fields

Very high-energy gamma-ray beams traveling over extragalactic distances are a unique laboratory for studying properties of photons, to constrain theories that describe spacetime at the Planck scale and for testing radiation fields of cosmological origin. The potential for probing the cosmic infrared background with TeV photons was first pointed out by Gould and Schréder [70] and was revived by Stecker, de Jager & Salamon [10], inspired by the detection of extragalactic TeV gamma-ray sources in the nineties. High-energy gamma rays traveling cosmological distances are attenuated en route to Earth by $\gamma + \gamma \rightarrow e^+ + e^-$ interactions with photons from the extragalactic background light. While the Universe is transparent for gamma-ray astronomy with energies below 10 GeV, photons with higher energy are absorbed by diffuse soft photons of wavelengths short enough for pair production. Photons from the EBL in the 0.1 to 20 micron wavelength range render the Universe opaque in TeV gamma rays, similarly to the cosmic microwave background that constitutes a barrier for 100 TeV photons. The transition region from an observational window turning opaque with increasing gamma-ray energy provides the opportunity for deriving observational constraints to the intervening radiation field. Whereas the cosmic microwave background is accessible via direct measurements, the cosmic infrared background (CIB) has been elusive and remains extremely difficult to discern by direct measurements. Energy spectra of extragalactic gamma-ray emitters between 10 GeV to 100 TeV allow us to extract information about the diffuse radiative background using spectroscopic measurements. Non-thermal gamma-ray emission spectra often extend over several orders of magnitude in energy and the high-energy absorption features expected from pair production can be adequately resolved with the typical energy resolution of 10% to 20% achievable with atmospheric Cherenkov telescopes.

The EBL, spanning the UV to far-infrared wavelength region, consists of the cumulative energy releases in the Universe since the epoch of recombination (see [71] for a review). The EBL spectrum comprises of two distinct components. The first, peaking at optical to near-infrared wavelengths (0.5-2 μm), consists of primary redshifted stellar radiation that escaped the galactic environment either directly or after scattering by dust. In a dust-free Universe, the SED of this component can be simply determined from knowledge of the spectrum of the emitting sources and the cosmic history of their energy release. In a dusty Universe, the total EBL intensity is preserved, but the energy is redistributed over a broader spectrum, generating a second component consisting of primary stellar radiation that was absorbed and reradiated by dust at infrared (IR) wavelengths. This thermal emission component peaks at wavelengths around 100 to 140 μm. The EBL spectrum exhibits a minimum at mid-IR wavelengths (10 - 30 μm), reflecting the decreasing intensity of the stellar contribution at the Rayleigh-Jeans part of the spectrum, and the paucity of very hot dust that can radiate at these wavelengths.

All energy or particle releases associated with the birth, evolution, and death of stars can ultimately be related to or constrained by the intensity or spectral energy distribution (SED) of the EBL. The energy output from AGN represent a major non-nuclear contribution to the radiative energy budget of the EBL. Most of the radiative output of the AGN emerges at X-ray, UV, and optical wavelengths. However, a significant fraction of the AGN output can be absorbed by dust in the torus surrounding the accreting black hole, and reradiated at IR wavelengths. In addition to the radiative output from star forming galaxies and AGN, the EBL may also harbor the radiative imprint of a variety of "exotic" objects including Population III stars, decaying particles, and primordial massive objects. EBL measurements can be used to constrain the contributions of such exotic components.

Direct detection and measurements of the EBL are hindered by the fact that it has no distinctive spectral signature, by the presence of strong foreground emission from the interplanetary (zodiacal) dust cloud, and from the stars and interstellar medium of the Galaxy. Results obtained from TeV gamma-ray observations will complement the results from a number of NASA missions, i.e. Spitzer, Herschel, the Wide-Field Infrared Survey Explorer (WISE), and the James Webb Space Telescope (JWST). In order to derive the EBL density and spectrum via gamma-ray absorption, ideally one would use an astrophysical standard candle of gamma rays to measure the absorption component imprinted onto the observed spectrum. In contrast, extragalactic TeV gamma-ray sources detected to date are highly variable AGN. Their gamma-ray emission models are not unanimously agreed upon, making it impossible to predict the intrinsic source spectrum. Therefore, complementary methods are required for a convincing detection of EBL attenuation. Various approaches have been explored to constrain/measure the EBL intensity [10, 72, 73, 74, 75, 76], ranging from searching for cutoffs, the assumption of plausible theoretical source models, the possibility of using contemporaneous X-ray to TeV measurements combined with emission models and the concept of simultaneous constraints from direct IR measurements/limits combined with TeV data via exclusion of unphysical gamma-ray spectra. All of these techniques are useful; however, none has so far provided an unequivocal result independent of assumed source spectra.

The next-generation gamma-ray experiments will allow us to use the flux and spectral variability of blazars [77, 78, 79] to separate variable source phenomena from external persistent spectral features associated with absorption of the gamma-ray beam by the EBL. Redshift dependent studies are required to distinguish possible absorption by radiation fields nearby the source from extragalactic absorption. The most prominent feature of blazars is their occasional brightness (sometimes $>$ 10 Crab) yielding a wealth of photon statistics. Those flares are to date the most promising tests of the EBL density based on absorption. To constrain the EBL between the UV/optical all the way to the far IR a statistical sample of gamma-ray sources, and a broader energy coverage with properly matched sensitivity are required.

Since the cross-section for the absorption of a given gamma-ray energy is maximized at a specific target photon wavelength (e.g., a 1 TeV gamma-ray encounters a 0.7 eV soft photon with maximum cross-section), there is a natural division of EBL studies with gamma rays into three regions: the UV to optical light, the near- to mid-IR and the mid- to far-IR portion of the EBL are the most effective absorbers for $\approx$ 10 - 100 GeV, the $\approx$ 0.1 TeV to 10 TeV and the $\approx$ 10 - 100 TeV regime, correspondingly.

In the search for evidence of EBL absorption in blazar spectra it is important to give consideration to the shape of the EBL spectrum showing a near IR peak, a mid IR valley and a far IR peak; absorption could imprint different features onto the observed blazar spectra. For example, a cutoff from the rapid increase of the opacity with gamma-ray energy and redshift is expected to be most pronounced in an energy spectral regime that corresponds to a rising EBL density; e.g., as is found between 0.1 - 2 micron. This corresponds to gamma ray energies of 10 GeV - 100 GeV. A survey with an instrument with sensitivity in the 10 GeV to several 100s of GeV could measure a cutoff over a wide range of redshifts and constrain the UV/optical IR part of the EBL. Fermi, together with existing ground-based telescopes, is promising in yielding first indications or maybe first conclusive results for a detection of the EBL absorption feature. However, an instrument with a large collection area over the given energy range by using the ground-based gamma-ray detection technique would allow stringent tests via spectral variability measurements.

Similarly, a substantial rise in the opacity with gamma-ray energy is expected in the energy regime above 20 TeV, stemming from the far IR peak. A corresponding cutoff should occur in the 20-50 TeV regime. Prospective candidate objects are Mrk 421, Mrk 501 or 1ES1959+650, as they provide episodes of high gamma-ray fluxes, allowing a search for a cutoff with ground-based instruments that have substantially enlarged collection areas in 10 - 100 TeV regime. Sensitivity for detection of a cutoff in this energy regime requires IACTs with a collection area in excess of 1km^2.

Finally, a promising and important regime for ground-based telescopes to contribute to EBL constraints lies in the near and the mid IR (0.5 -

5 micron). The peak in the near IR and the slope of decline in the mid IR could lead to unique spectral imprints onto blazar spectra around 1-2 TeV, assuming sufficient instrumental sensitivity. A steep decline could lead to a decrease in opacity, whereas a minimal decline could result in steepening of the slope of the source spectrum. If this feature is sufficiently pronounced and/or the sensitivity of the instrument is sufficient, it could be a powerful method in unambiguously deriving the level of absorption and discerning the relative near to mid IR density. The location of the near IR peak and, consequently, the corresponding change in absorption, is expected to occur around 1.5 TeV, which requires excellent sensitivity between 100 GeV and 10 TeV. The discovery of a signature for EBL absorption at a characteristic energy would be extremely valuable in establishing the level of absorption in the near to mid IR regime. The origin of any signature could be tested using spectral variations in blazar spectra and discerning a stable component.

A powerful tool for studying the redshift dependence of the EBL intensity are pair haloes [80]. For suitable IGMF strengths, such haloes will form around powerful emitters of >100 TeV gamma rays or UHECRs, e.g. AGN and galaxy clusters. If the intergalactic magnetic field (IGMF) is not too strong, the high-energy radiation will initiate intergalactic electromagnetic pair production and inverse Compton cascades. For an intergalactic magnetic field (IGMF) in the range between 10^{-12} G and 10^{-9} G the electrons and positrons can isotropize and can result in a spherical halo glowing predominantly in the 100 GeV – 1 TeV energy range. These haloes should have large extent with radial sizes > 1 Mpc. The size of a 100 GeV halo surrounding an extragalactic source at a distance of 1 Gpc could be less than 3° and be detectable with a next-generation IACT experiment. The measurement of the angular diameter of such a halo gives a direct estimate of the local EBL intensity at the redshift of the pair halo. Detection of several haloes would thus allow us to obtain unique information about the total amount of IR light produced by the galaxy populations at different redshifts.

For a rather weak IGMF between $\sim 10^{-16}$ G and $\sim 10^{-24}$ G, pair creation/inverse Compton cascades may create a GeV/TeV "echo" of a TeV GRB or AGN flare [81]. The IGMF may be dominated by a primordial component from quantum fluctuations during the inflationary epoch of the Universe, or from later contributions by Population III stars, AGN, or normal galaxies. The time delay between the prompt and delayed emission depends on the deflection of the electrons by the IGMF, and afford the unique possibility to measure the IGMF in the above mentioned interval of field strengths.

References

[1] Sreekumar, P., Bertsch, D. L., Hartman, R. C. et al. 1999, Astroparticle Physics, 11, 221

[2] Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R. et al. 2006, Science, 314, 1424

[3] Tavecchio, F. 2005, The Tenth Marcel Grossmann Meeting. , 512

[4] Krawczynski, H. 2006, Astronomical Society of the Pacific Conference Series, 350, 105

[5] Hartman, R. C., et al. 1999, ApJS, 123, 79

[6] Punch, M., et al. 1992, Nature, 358, 477

[7] Fossati, G., Buckley, J., Edelson, R. A., Horns, D., & Jordan, M. 2004, New Astronomy Review, 48, 419

[8] Aharonian, F., et al. 2005, A&A, 441, 465

[9] Horan, D., & Weekes, T. C. 2004, New Astronomy Review, 48, 527

[10] Stecker, F. W., De Jager, O. C., & Salamon, M. H. 1992, ApJ, 390, L49

[11] Gaidos, J. A., et al. 1996, Nature, 383, 319

[12] Buckley, J. H., et al. 1996, ApJ, 472, L9

[13] Takahashi, T., et al. 1996, ApJ, 470, L89

[14] S.C. Unwin, A.E. Wehrle, D.L. Jones, D.L. Meier, and B.G. Piner, 2002, Publ. of the Astronomical Society of Australia, 19, 5

[15] J.E. Grindlay, 2005, New Astron.Rev., 49, 436

[16] Krawczynski, H., Coppi, P. S., Maccarone, T., & Aharonian, F. A. 2000, A&A, 353, 97

[17] Georganopoulos, M., Perlman, E. S., Kazanas, D., & McEnery, J. 2006, ApJ, 653, L5

[18] Blandford, R. D. 1976, MNRAS, 176, 465

[19] Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433

[20] Lovelace, R. V. E. 1976, Nature, 262, 649

[21] Levinson, A. 2000, Physical Review Letters, 85, 912

[22] Krawczynski, H. 2007, ApJ, 659, 1063

[23] Romanova, M. M., & Lovelace, R. V. E. 1997, ApJ, 475, 97

[24] Fossati, G., et al. 2008, ApJ, 677, 906

[25] Kundt, W., Gopal, K. 2004, JApA, 25, 115

[26] De Young, D. 2006, ApJ, 648, 200

[27] Noguchi, K., & Liang, E. 2007 , Astrophys. & Space Sci., 307, 315

[28] Nishikawa, K.-I., Hededal, C.B., Hardee, P.E., Fishman, G.J.,Kouveliotou, C., & Mizuno, Y. 2007,Astrophys. & Space Sci., 307, 319-323

[29] Lovelace, R.V.E., Gandhi, P.R., & Romanova, M.M. 2005, Astrophys. & Space Sci., 298, 115

[30] Chang, P., Spitkovsky, A., & Arons, J. 2008, ApJ, in press (arXiv:0704.3832v1)

[31] Aharonian, F. A. 2000, New A, 5, 377

[32] Mücke, A., & Protheroe, R. J. 2001, Astroparticle Physics, 15, 121

[33] Mücke, A., Protheroe, R. J., Engel, R., Rachen, J. P., & Stanev, T. 2003, Astroparticle Physics, 18, 593

[34] Mannheim, K. 1993, A&A, 269, 67

[35] Lovelace, R. V. E., MacAuslan, J., & Burns, M. 1979, AIP Conf. Proc. 56: Particle Acceleration Mech. in Astrophys., 56, 399

[36] Burns, M. L., & Lovelace, R. V. E. 1982, ApJ, 262, 87

[37] Blandford, R. D., & Levinson, A. 1995, ApJ, 441, 79

[38] Levinson, A., & Blandford, R. 1995, ApJ, 449, 86

[39] Halzen, F., Hooper, D., 2005, Astropart.Phys., 23, 537

[40] Strong, A., Moskalenko, I. V., Reimer, O. 1999, Proc. 26th Int. Cosmic Ray Conf. (Salt Lake), 4, 52

[41] Aharonian, F., et al. 2006, Nature, 439, 695

[42] Sreekumar, P., et al. 1992, ApJ, 400, L67

[43] Völk, H. J., Aharonian, F. A., Breitschwerdt, D. 1996, Space Science Reviews, 75, 279

[44] Pohl, M. 1994, A&A, 287, 453

[45] Nagai, T. 2005, Ph.D. Thesis, UCLA

[46] Itoh, C., et al. 2002, A&A, 396, L1

[47] Aharonian, F., et al. 2005, A&A, 442, 177

[48] Torres, D. F., Reimer, O., Domingo-Santamaría, E., Digel, S. W. 2004, ApJ, 607, L99

[49] Torres, D. F. 2004, ApJ, 617, 966

[50] Völk, H. J., Atoyan, A. M. 1999, Astroparticle Physics, 11, 73

[51] Ensslin, T. A., Biermann, P. L. 1998, A&A, 330, 90

[52] Keshet, U., et al. 2003, ApJ, 585, 128

[53] Gabici, S., Blasi, P. 2004, Astroparticle Physics, 20, 579

[54] Perkins, J. S., et al. 2006, ApJ, 644, 148

[55] Domainko, W., Benbow, W., Hinton, J.A. , et al. 2007, Proc. of the 30th ICRC, Merida, Mexico

[56] Berrington, R. C., Dermer, C. D. 2005, eprint arXiv:astro-ph/0407278

[57] Reimer, A., et al. 2004, A&A, 424, 773

[58] Rordorf, C., Grasso, D., Dolag, K. 2004, Astroparticle Physics, 22, 167

[59] Miniati, F. 2003, MNRAS, 342, 1009

[60] V. Van Elewyck, Proc. Int. School of Cosmic Ray Astrophysics, 15th Course, Erice, Italy, 20-27 June 2006, astro-ph/0612731

[61] Gabici, S., & Aharonian, F. A. 2005, Physical Review Letters, 95, 251102

[62] Atoyan, A., and Dermer, C. 2003, ApJ, 586, 79

[63] Aharonian, F., et al., ApJL, 664, L71 (2007)

[64] Krawczynski, H., et al., ApJ, 559, 187 (2001)

[65] Begelman, M. C., Fabian, A. C., and Rees, M. J., MNRAS, 384, L19 (2008)

[66] Fossati, G., et al., ApJ, 677, 906 (2008)

[67] Marscher, A. P., et al., Nature, 452, 966 (2008)

[68] Spruit, H. C., ArXiv e-prints, 0804.3096 (2008)

[69] Teshima, M., et al., ArXiv e-prints, 0709.1475 (2007)

[70] Gould, R. J., & Schrèder, G. 1967, Phys. Rev., 155, 1408

[71] Hauser, M.G., & Dwek, E. 2001, ARA & A, 39, 249

[72] Biller, S.D. et.al. 1995, ApJ 445, 227

[73] Vassiliev, V.V. 2000, Astroppart. Phys., 12, 217

[74] Dwek, E., Krennrich, F. & Arendt, R. 2005, ApJ 634, 155

[75] Aharonian, F., et al. 2006, Nature, 440, 1018

[76] Mazin, D., & Raue, M. 2007, astro-ph/0701694

[77] Coppi, P. S., & Aharonian, F. A. 1999, Astroparticle Physics, 11, 35

[78] Krennrich, F. et al. 2002, ApJ, 579, L9

[79] Aharonian, F., et al. 2002, A&A, 393, 89

[80] Aharonian, F. A., Coppi, P. S., & Voelk, H. J. 1994, ApJ, 423, L5

[81] Plaga, R. 1995, Nature, 374, 430