Science Potential of Extragalactic VHE γ-ray Observations

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The field of Very High Energy (VHE; E>100 GeV) γ-ray astronomy has made astonishing progress in the past decade, as third-generation VHE experiments such as H.E.S.S., MAGIC, and VERITAS were constructed and began operations. These experiments, arrays of imaging atmospheric-Cherenkov telescopes, have produced breathtaking results from many newly discovered Galactic VHE γ-ray emitters, including spatially and spectroscopically resolved images of supernova remnants and pulsar wind nebulae. In the extragalactic domain, VHE γ-ray emission is observed from dozens of blazars as well as the radio galaxies M 87 and Cen A. Rapid VHE flux and spectral variability detected from these objects implies emission regions near to, and comparable in size to, the event horizon of their central supermassive black hole and reveals key information regarding their powerful accretion-driven engines. At lower energies, the Fermi γ-ray Space Telescope, a satellite-borne MeV-GeV γ-ray detector, is currently enlarging the sample of Galactic and extragalactic γ-ray sources. It is expected to discover more than one thousand extragalactic γ-ray emitters and will likely reveal new classes of extragalactic γ-ray emitting objects beyond Active Galactic Nuclei (AGN). What drives these astrophysical systems, capable of particle acceleration beyond that possible in Earth-based accelerators, is one of the key science questions of our times. Recent experiments have established γ-ray astronomy as a rich and rewarding scientific discipline. A next-generation ground-based VHE γ-ray observatory like AGIS[1] or CTA[2] will achieve a sensitivity of 10^{-13} erg cm^{-2} s^{-1}, an order of magnitude improvement over current experiments, enabling the study extragalactic γ-ray sources with unprecedented detail and likely opening many new avenues for exploration.

In this white paper the potential of a next-generation VHE γ-ray experiment to reveal key insights into several types of extragalactic objects, especially AGN, is summarized. A more detailed discussion is found in [1]. The key science questions addressed are:

- How do supermassive black holes accrete, grow, and form powerful jets?
- What are AGN jets made of, and how are they structured?
- What role do cosmic rays play in other galaxies and galaxy clusters?
- What do γ-rays reveal about the largest structures in the Universe?
- What is the origin of ultra-high-energy comic rays (UHECR)?
- What is the star-formation history of the Universe?

[1] http: //www.agis-observatory.org
[2] http: //www.cta-observatory.org

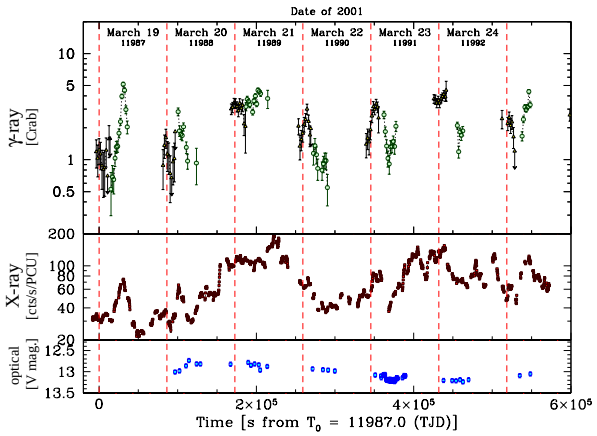

Figure 1: VHE, X-ray and optical light curve of Mkn 421 in 2001. Results from Rossi X-ray Timing Explorer (RXTE) 2-4 keV X-ray, Whipple (full symbols) and HEGRA (open symbols) VHE γ-ray, and Mt. Hopkins 48-inch optical observations [6]. The X-ray/VHE fluxes are correlated. However, the interpretation of the data is hampered by sparse VHE γ-ray coverage.

1 Jets and Supermassive Black Holes

AGN are found at the centers of $\sim$5% of all galaxies and are strong emitters of electromagnetic radiation over a range of more than 20 decades in energy. These objects contain a central supermassive black hole (SMBH) having a mass between a million and several billion solar masses, and $\sim$10% of AGN possess kpc-scale collimated outflows of particles and plasma called jets. Observations with *EGRET* on board of the Compton Gamma-Ray Observatory (CGRO) revealed that a certain class of AGN known as blazars (i.e those with jets pointed towards the observer) are powerful and variable emitters of $\geq$100 MeV γ-rays, similar to their behavior at radio through X-ray wavelengths. Observations with ground-based Cherenkov telescopes show that blazars surprisingly also emit VHE (E>100 GeV) γ-rays. More than twenty blazars, with redshifts ranging from 0.031 (Mkn 421) to 0.536 (3C 279), are identified as sources of VHE γ-rays[3] [3]. Most VHE bright sources are BL Lac type objects, the low-luminosity counterparts of the extremely powerful quasars detected by EGRET. The five non-blazar AGN known to emit γ-rays are located in radio galaxies and have jets that are oriented at larger angles towards the observer than blazars. A next generation VHE observatory is expected to detect copious numbers of blazars (quasars and BL Lac objects) and radio galaxies, thus enabling an understanding of these objects and their related science based on population studies.

The MeV to VHE γ-ray emission from blazars is believed to originate in their jets, which are powered by mass accreting onto the SMBH. The rapid γ-ray and X-ray flux variability of blazars, on time scales as low as $\sim$2 minutes, together with their high γ-ray and optical fluxes implies the jet outflow is extremely relativistic with a bulk Lorentz factor most likely in the range between 10 and 50 [4, 5], and possibly exceeding 100. Gamma-ray observations thus enable the study of plasma moving with $\geq$99.98% of the speed of light. Simultaneous broadband multiwavelength observations of blazars reveal a pronounced correlation of the X-ray and VHE γ-ray fluxes (see Fig. 1). This suggests the emitting particles are electrons radiating synchrotron emission in the radio to X-ray band and powering inverse-Compton emission in the γ-ray band.

The interpretation of blazar observations is currently hampered by model degeneracies. For example, several leptonic models of blazar emission, as well as some hadronic models, provide suitable explanations of the data. Timing and spectral data from a γ-ray observatory with improved AGIS or CTA-like sensitivity, especially when combined with other multi-wavelength observations, is key for breaking these degeneracies and unambiguously identifying the emission mechanism. The fastest variability observed in blazars is in the VHE band, and a gamma-ray observatory with improved sensitivity would enable the sampling of the γ-ray flux and spectrum

[3]Up-to-date VHE source lists: http: //tevcat.uchicago.edu and http: //www.mpp.mpg.de/ $\sim$rwagner/sources

on time scales as short as seconds. Indeed the flux and spectrum could be measured rapidly, even when the sources are not flaring, resolving any inherent flux variability.

Two recent observation campaigns highlight the diagnostic power of γ-ray observations when combined with imaging and polarimetry observations:

- Marscher et al. combine VLBA observations with optical polarimetry, X-ray, and VHE γ-ray data on the object BL Lac [7]. Following a strong X-ray/VHE γ-ray flare, an optical outburst with a continuous swing of the optical polarization direction and a brightening of the radio core is observed. The authors postulate that these effects are produced by a plasma knot that brightens as it is accelerated by the helical magnetic field of the jet.
- During strong day-scale VHE γ-ray flaring activity observed by VERITAS in the radio galaxy M 87, an extraordinary brightening of the radio core was contemporaneously observed by VLBA [8]. This indicates the γ-rays originate within the central resolution element of the VLBA observations, less than 50-100 Schwarzschild radii away from the black hole.

With current experiments, the VHE detection of radio galaxies like M 87 requires a long exposure, and VHE measurements of BL Lac are only possible during flaring episodes. A next-generation VHE γ-ray observatory like AGIS, with a factor of 10 improvement in sensitivity, would be able to routinely and rapidly sample the γ-ray spectrum of objects like BL Lac and M 87. These observations would also benefit from additional multi-wavelength coverage with future experiments like the Space Interferometry Mission (SIM)[4]. SIM can localize emerging plasma blobs with an accuracy of a few micro-arcsec. In the case of M 87, 10 micro-arcsec translates to a projected distance of 10^{15} cm, or 2 Schwarzschild radii of its $3{\times}10^9$ $M_\odot$ black hole. The SIM observations could thus image the blobs that give rise to the flares detected in the γ-ray regime as soon as they become optically thin. X-ray polarimetry experiments like the proposed Gravity and Extreme Magnetism SMEX (GEMS) mission or a similar focal plane instrument on the International X-ray Observatory (IXO) could probe the polarization of the soft X-rays of bright blazars. Combining the X-ray fluxes, energy spectra, polarization degree and polarization direction with the γ-ray fluxes and energy spectra would enable detailed tests of models of jet formation that include detailed descriptions of the geometry and structure of the jets. Joint multi-wavelength observations including hard X-ray observatories like NuStar[5], ASTRO-H[5], and/or EXIST[5], the Fermi γ-ray Space Telescope, and next-generation VHE γ-ray telescopes would sample the synchrotron and inverse-Compton emission from blazars over more than nine decades in frequency. Such observations would allow sensitive tests of leptonic and hadronic models and would enable studies of particle acceleration and turbulence in relativistic plasmas.

Gamma-ray observations will not only constrain the physics of the central core of AGN jets, but also of the kpc-scale jet emission (see, e.g., [9] or [10]). For example, the electrons that produce the large-scale IR and X-ray emission in the jet, should also produce a hard steady GeV and VHE component. The observation or non-observation of such a steady component can be used to constrain the bulk Lorentz factor of the kpc-scale jet material, as has been done in the case 3C 273.

Massive Dark Objects (MDOs), thought to be spinning black holes, are the $> 10^9$ $M_\odot$ masses located at the centers of many dormant, old AGN. Some of these objects are nearby (< 50 Mpc) and have been proposed as the sources for UHECRs ($> 10^{20}$ eV). If UHECRs are accelerated at these locations, then MDOs should emit a detectable flux of VHE γ-rays from curvature radiation of the protons in their magnetic fields.

[4]http: //planetquest.jpl.nasa.gov/SIM

[5]http: //www.nustar.caltech.edu; http: //ASTRO-H.isas.jaxa.jp; http: //exist.gsfc.nasa.gov

2 Cosmic Rays in Star-Forming Galaxies

More than 60% of the photons detected by EGRET were produced as a result of interactions between cosmic rays (CRs) and galactic interstellar gas and dust. Recently the H.E.S.S. collaboration reported the detection of diffuse VHE γ-ray radiation from the region of dense molecular clouds in the innermost 200 pc around the Galactic Center, confirming the theoretical expectation that hadronic CRs could produce VHE radiation in their interactions with atomic or molecular targets. A next-generation VHE observatory could map GeV-PeV CRs in Local Group galaxies, e.g. M 31, and study diffuse radiation from more distant extragalactic objects, provided their γ-ray luminosity is enhanced by a factor $\geq$10 over that of the Milky Way.

Nearby starburst galaxies (SBGs), such as NGC 253, M 82, IC 342, M 51 exhibit regions of strongly enhanced star formation and hence a high rate of supernova (SN) explosions. They also contain gas clouds that are up to 10^5 times more dense than the average Milky Way gas density. This combination creates nearly ideal conditions for the generation of intense, diffuse VHE radiation, assuming that efficient hadronic CR production takes place in the sites of the SN (i.e. that the SN origin of galactic CR paradigm is valid) and in colliding OB stellar winds [11]. In addition, leptonic gamma-ray production through inverse-Compton scattering in regions of high-density photons produced by OB associations may become effective in star forming regions [12]. The theoretical expectation of VHE radiation from SBG is not yet confirmed by H.E.S.S., MAGIC, and VERITAS, although predictions suggest that continued observations with these instruments will eventually lead to the discovery of a few SBGs at distances less than $\sim$10 Mpc. A next-generation γ-ray observatory should discover $\sim$100 of these objects within a visibility range of $\sim$ 100 Mpc. Thus SBGs could be used as laboratories for the detailed study of the SNR CR acceleration paradigm, as well as the VHE phenomena associated with star formation.

If accelerated CRs are confined in 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 γ-ray flux will not be enhanced by an increased density of target material. However, an increased SN rate could provide this enhancement. Ultra Luminous InfraRed Galaxies (ULIRGs) have SN rates on the scale of a few per year (compared to the Milky Way rate of $\sim$1 per century) and very large amounts of molecular material, and as a result are potentially detectable γ-ray sources. Although they are located at distances between ten and a hundred times farther than the most promising SBGs, the ULIRGs Arp 220, IRAS 17208, and NGC 6240 may be within the range of being detected by the Fermi γ-ray Space Telescope, VERITAS and H.E.S.S. [13]. Next-generation γ-ray instruments might be able to detect the most luminous objects of this type even if they are located at $\sim$1 Gpc distances. Initial studies of the population of ULIRGs indicate that these objects underwent significant evolution through the history of the Universe, and that at a moderate redshift ($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 γ-ray luminosity of these objects and their luminosity evolution. However, if theoretical predictions for Arp 220 are representative for ULIRGS, then >100 may be detectable.

The scientific drivers for the study of ULIRGs and SBGs include research of galaxy γ-ray emissivity as a function of target gas density, supernova rate, confining magnetic field, etc. In addition, research of ULIRGs offers 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. Accumulating evidence suggests that AGN feedback mechanisms connect episodes of intense starbursts in galaxies with central black hole accretion activity. These processes have been detected from dozens of ULIRGs and new insight into this phenomenon may be obtained by the observation of their VHE counterparts.

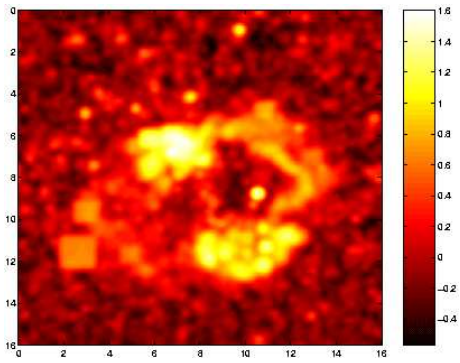

Figure 2: Results from a cosmological simulation showing how the >10 GeV γ-ray emission from a nearby galaxy cluster could look like when mapped with a γ-ray telescope with 0.2° angular resolution. The image covers a 16° × 16° region (color scale: $\log(J/\bar{J})$ for an average >10 GeV flux of $\bar{J}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

3 The Largest Particle Accelerators in the Universe

Galaxy clusters (GCs) are the largest gravitationally bound objects in the Universe and the possibility of observing diffuse GeV and TeV radiation from them is widely discussed in the literature. In GCs, collisionless structure-formation shocks, triggered by the accretion of matter or galaxy mergers, are likely the main agents responsible for heating the inter-cluster medium (ICM) to temperatures of ∼10 keV. Through these processes a fraction of the gravitational energy is converted into the kinetic energy of non-thermal particles: protons and electrons. Galactic winds [14] and re-acceleration of mildly-relativistic particles injected into the ICM by powerful cluster members [15] may accelerate additional particles to non-thermal energies. As cosmic-ray protons can only escape clusters on time scales much longer than the Hubble time, they accumulate over the entire history of the cluster [14], and eventually interact with the intercluster thermal plasma to produce VHE γ-ray radiation. Theoretical predictions for the detection of such systems by VERITAS and H.E.S.S. include clusters in the range from $z = 0.01$ to $z = 0.25$ (see Fig. 2) [11, 16, 17]. Multiple attempts to find γ-ray signals from GCs in EGRET, HESS and VERITAS data have failed. If nearby representatives of the GC class are eventually detected, a next-generation VHE γ-ray observatory would be able to obtain spatially resolved energy spectra from the close, high-mass systems, and should be able to obtain fluxes and energy spectra for several dozen additional clusters. The detection of γ-ray emission from galaxy clusters would make it possible to study acceleration mechanisms on large scales (>10 kpc). It would permit the measurement of the energy density of non-thermal particles and the investigation of their influence on 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 γ-ray fluxes from GCs, the correlation of γ-ray luminosity and spectrum with cluster mass, temperature, and redshift could also be explored. If such correlations are found, it might be possible to use GCs as "standard candles" to measure the diffuse infrared and visible radiation of the Universe through pair-production attenuation of γ-rays as discussed in Section 4.

Large-scale structure formation shocks could accelerate protons and high-energy electrons out of the intergalactic plasma. 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. Cosmic Microwave Background (CMB) photons inverse-Compton scattered by these electrons may reach VHE γ-ray energies. As the energy gained by the scattered photons rapidly cools electrons, their range is limited to regions close to the accelerating shocks. Simulations predict that the flux of γ-rays from these shocks may be detectable by the current generation of VHE telescopes [18]. This is possibly 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.

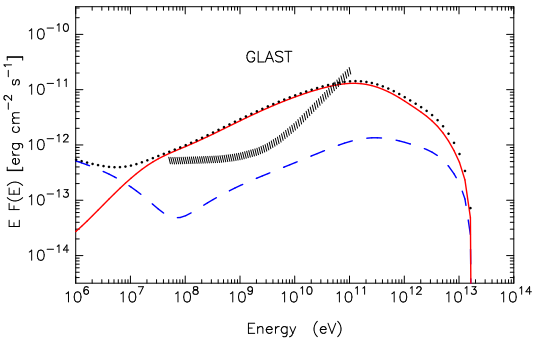

Figure 3: Fluxes from the electromagnetic cascade initiated in Cyg A by UHECRs assuming the total power injected by secondary UHE electrons and γ-rays at $\leq$ 1 Mpc distances of about 10^{45} erg/s (from [19]). The solid and dashed lines show the synchrotron and Compton fluxes, respectively. The sensitivity of a next-generation VHE observatory, e.g. AGIS, is expected to reach 10^{-13} erg cm^{-2} s^{-1}.

Since 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, despite the low gas densities involved.

The origin of ultra-high-energy cosmic rays (UHECRs, $E \gtrsim 10^{16}$ 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 AGN. Gamma-ray observations may be ideally suited to study this acceleration process, as the UHECRs must produce γ-rays through various processes on scales of a few pc to several hundred kpc. For example, the interaction of UHECR with photons from the CMB creates secondary γ-rays and electrons/positrons. Depending on the strength of the intergalactic magnetic field ($B_{\rm IGMF}$), a next-generation ground-based γ-ray experiment could detect VHE γ-rays from synchrotron emission of first generation electrons/positrons ($B_{\rm IGMF} \geq 10^{-9}$ G), or inverse-Compton radiation from an electromagnetic cascade ($B_{\rm IGMF} \leq 10^{-9}$ G) [20]. Figure 3 shows γ-ray fluxes expected from Cyg A by injecting 10^{45} erg/s of secondary electrons and/or $\gamma-$rays from GZK protons. From these processes Cyg A should be a moderately extended VHE source or halo (r<14'), detectable by a next-generation VHE observatory. The detection of such emission could give information about the $\gg$TeV luminosity of these sources and the strength of the intergalactic magnetic fields (IGMF).

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 distributions of such halos will contain crucial information about the IGMF.

4 Constraining the Star-Formation History of the Universe

The diffuse extragalactic background light (EBL) consists of the combined flux of all extragalactic sources integrated over the entire history of the universe (see [21] for a review). As a result its calorimetric information carries unique information about the epochs of galaxy formation and the history of galaxy evolution, and is of significant interest to cosmologists. Unfortunately, direct measurements of its wavelength-dependent density are both difficult and subject to large systematic errors, particularly in the mid-IR, primarily due to the model-dependent subtraction of the overwhelming amounts of foreground light originating in our Solar System and Galaxy. A very promising measurement technique is the study of absorption features [22] imprinted in the VHE γ-ray spectra of distant extragalactic objects by interactions of those photons with optical and infrared EBL photons (see, e.g., [23]). By comparing observed VHE spectra with those expected from models, a measurement of the optical depth, τ(E,z), can be made. As the optical depth is calculated directly from an integral of the EBL density, the EBL spectral energy distribution is thus measured. In many respects the use of extragalactic VHE spectra is the only reliable method for probing the EBL in the mid-IR, which in some ways is analogous

to the CMB. The detection of large quantities and several classes of extragalactic objects, with a large spread in redshift, is expected with a next-generation VHE instrument. This will enable model-independent measurements of the optical and IR EBL density for the first time.

5 Concluding Remarks

The anticipated discovery of additional extragalactic sources by VERITAS, H.E.S.S. and the Fermi γ-ray Space Telescope will put the theoretical predictions discussed here on firmer ground. If the origin of γ-ray radiation in these sources is hadronic, the Fermi γ-ray Space Telescope should detect most of the SBGs, ULIRGs, and GCs, potentially detected by a VHE observatory. However, in scenarios with leptonic γ-ray mechanisms many such sources (e.g. M 82) may escape Fermi γ-ray Space Telescope detection. These may still be detectable with VHE instruments. In addition, it is likely that diffuse extragalactic γ-ray sources will be discovered by the Fermi γ-ray Space Telescope, and a program to identify these sources using narrow field-of-view VHE observatories will be useful. The Fermi γ-ray Space Telescope will also measure the Galactic and extragalactic γ-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 γ-ray sources to the extragalactic background in the range above a few GeV to $\sim$100 GeV is best accomplished by the next-generation ground-based instrument, capable of detecting a large number of sources rather than a few. Finally it should again be stressed that the extragalactic background in the optical to mid-IR is perhaps best constrained by measuring EBL-absorption effects on multiple distant sources of $\sim$TeV photons, a task only possible with the very large collection areas of ground-based VHE observatories.

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