The Status of H.E.S.S. and CTA, and Their Role in a Multiwavelength Context

C. Venter

Centre for Space Research, North-West University, Potchefstroom Campus, Private Bag X6001,
Potchefstroom 2520, South Africa
Christo.Venter@nwu.ac.za

Abstract: The High Energy Stereoscopic System (H.E.S.S.) is a world-class experiment located in Namibia and consists of an array of four 13-m telescopes which investigate the non-thermal universe in the 100 GeV to 100 TeV energy range via the Cherenkov technique. H.E.S.S. is sensitive to fluxes of a few thousandths of that of the Crab Nebula, has a wide field of view (FoV; 5°), sub-degree angular resolution ($< 0.1^\circ$), accurate pointing ($< 10''$), and good spectral resolution (10–20%). Its excellent location affords a clear view of the Galactic Centre as well as many Galactic sources. H.E.S.S. Phase II, entailing the addition of a 28-m central telescope to the existing four, is already underway. This will result in increased energy coverage (with an expected threshold of $\sim$20 GeV), sensitivity, and angular resolution. Efforts towards the design and construction of a next-generation gamma-ray observatory called the *Cherenkov Telescope Array* (CTA) are gaining momentum. This will consist of a northern and southern component, unifying the global gamma-ray astronomy community, and will boast an order-of-magnitude increase in sensitivity. The status of the Southern African site bid for hosting CTA-South is discussed. Lastly, it is important to view our knowledge of the very-high-energy (VHE) sky within the greater multiwavelength context, it being complementary to observations at lower energies (e.g., high-energy gamma rays, X-rays, optical, and radio waves). The rich opportunities created by such a synergy will bolster the continued study of some of the most violent and energetic phenomena in the Universe.

This paper is dedicated to the memory of Okkie de Jager, whose enthusiasm, knowledge, insight and warm personality are sorely missed.

Introduction

There has recently been great progress in multiwavelength astronomy, including that in the developing world. Exciting advances over the past few years include the construction and / or operation of the *High Energy Stereoscopic System* (H.E.S.S.), the *Southern African Large Telescope* (SALT), and the *Karoo Array Telescope* (MeerKAT). South Africa is also shortlisted as a potential host country for the *Square Kilometre Array* (SKA), which will be the largest and most sensitive radio telescope ever built. Within this context (and in line with the aims of this conference*), the present paper will review the status of H.E.S.S. and its next-generation follow-up experiment, the *Cherenkov Telescope Array* (CTA). It will also discuss the Southern African CTA site proposal, and point out examples of opportunities for cross-field collaboration by observers working in different electromagnetic wavebands. For more information, the reader is referred to the many excellent reviews on TeV gamma-ray astronomy.†

Background

The acronym H.E.S.S. was chosen in honour of the Nobel laureate Victor Hess, discoverer in 1912 of cosmic rays (CRs). The name also signifies that the electromagnetic domain of operation is gamma ray energies in the GeV to TeV range, and that the four telescopes are used stereoscopically, much like human eyes, to better determine the direction of an incoming gamma ray. The H.E.S.S. Collaboration is a multinational team consisting of more than 150 scientists from 12 countries. It has operated four 13-m Imaging Atmospheric Cherenkov Telescopes (IACTs), situated in the Khomas Hochland in Namibia at a height of 1800 m.a.s.l., since December 2003, investigating the non-thermal Universe in gamma rays via the Cherenkov technique. The latter entails the observation of faint, ultrafast bluish flashes of Cherenkov light resulting from the interaction of a gamma ray with the Earth's atmosphere and the subsequent formation of a cascade of relativistic particles that move faster than the speed (phase velocity) of light in air.[23] This technique has been significantly refined since the detection of the Crab Nebula as the first TeV source in 1989,[71] building on experience gained by the operation of various precursor experiments, including the *Whipple Observatory*, which pioneered the imaging principle, the *High Energy Gamma Ray Astronomy* (HEGRA) experiment, which first used stereoscopic technology, and the *Cherenkov Array at Themis* (CAT), which first employed finely-pixelated imaging.

The neutrality of gamma rays (and neutrinos) implies the preservation of their original direction as they reach the Earth, in contrast to the case of cosmic rays (CRs), which are deflected by the Galactic magnetic field, masking their natal location. Since gamma rays are produced by CR interactions, they represent a fundamental technique for indirectly probing the acceleration sites where CRs are produced[58] and also offer a new very-high-energy (VHE) window on the Universe. Apart from gamma-ray production by the decay of heavy particles, the only other way of generating these VHE photons is during the interactions of accelerated nuclei and leptons with ambient radiation or matter fields (e.g., via synchrotron radiation, inverse Compton scattering, Bremsstrahlung, or neutral pion decay). For these cases, the gamma-ray production rate depends on the product of particle (CR) and target (electromagnetic, radiation, or matter fields) densities. Studies of astrophysical gamma-ray sources furthermore include particle transport (e.g., acceleration, diffusion, convection) and lifetimes, deter-

---

[*] http://mearim2.saao.ac.za/index.php/scientific-rationale.html

[†] http://tevcat.uchicago.edu/reviews.html

mined by the energy losses they suffer.[51]

Key Performance Features of H.E.S.S.

Each of the four H.E.S.S. telescopes has a 960-pixel camera, and 380 mirror segments, yielding a 107 m^2 mirror area per telescope.[50] The high sensitivity of H.E.S.S. is evidenced by the fact that there are three orders of magnitude dynamic range in flux between the strongest and faintest source observed, and owing to efficient background rejection it can measure fluxes of up to a few thousandths of that of the Crab Nebula. The energy threshold[53] is ~ 100 GeV at the zenith, and increases to ~ 0.7 TeV at zenith angles of 60°. It has a wide spectral range spanning more than two orders of magnitude coverage in energy, up to tens of TeV, with an energy resolution of $10\% - 15\%$.[33] Its angular resolution ($< 0.1^\circ$), large field of view (FoV; 5°), and good pointing accuracy ($\sim 10''$),[10] yield a resolving power to study source morphology, as well as good source localisation ability. The time resolution of H.E.S.S. facilitates the measurement of well-resolved light curves,[72] e.g. enabling minute-scale variability studies of active galactic nuclei (AGN).[22] Lastly, its location and survey capability at $\sim 2\%$ Crab sensitivity affords a superb view of the Galactic Centre and many Galactic sources.

H.E.S.S. Source Classes

The combination of the superior location and experimental capabilities of H.E.S.S. has led to a long list of exciting discoveries of a number of VHE gamma-ray sources over the past few years, including supernova remnants (SNRs), the source at the Galactic Centre, compact binary systems, microquasars, pulsar wind nebulae (PWN), gamma rays from CR interactions with dense molecular clouds, a starburst galaxy, stellar clusters, AGN, and "dark sources" with no obvious counterparts at other wavelengths in the electromagnetic spectrum, in addition to conducting the first VHE survey of the sky, measuring the local CR electron and iron nuclei spectra, constraining the level of extragalactic background light (EBL), and providing upper limits to dark matter annihilation cross-sections.[‡] These feats have been recognised internationally: H.E.S.S. shared the 1 million Euro EU Descartes Prize for Research in 2006, and won the 2010 Rossi Prize of the High Energy Astrophysics Division (HEAD) of the American Astronomical Society (AAS) for revolutionising the field of gamma-ray astronomy. Below, only a few examples of particular H.E.S.S. sources are given. More detailed discussions may be found elsewhere.[43,51,54,63]

Galactic Plane Survey (GPS)

The original GPS consisted of 230 h of data, covering the inner Galaxy region (±30° in longitude and ±3° in latitude relative to the Galactic Centre).[21] The observation time has been substantially increased to over 2300 h, covering the longitude range 250° to 60°, and detecting more than 60 Galactic sources.[45]

Galactic Centre: HESS J1745-290

The source HESS J1745-290 was first discovered in VHE gamma rays in 2003 (16 h of data with two telescopes).[13] Initial observations obtained a source position which was consistent with both the central supermassive black hole (SMBH) Sag A* and the SNR Sag A East. Subsequent observations revealed the PWN in the shell-type SNR G0.9+0.1[15] as well as diffuse emission tracing the giant molecular clouds in our Galaxy's centre.[19] After five years of consistent efforts, the source position was shown to be within $8''$ of Sag A*, consistent with the SMBH, but inconsistent with the Sag A East SNR.[10] The absence of any flare in the VHE band during an X-ray one[27] complicates the question as to the actual source of these VHE gamma rays.[30]

Supernova Remnant: SN 1006

This historic supernova (SN) first appeared in the southern sky on 1 May 1006, as recorded by Chinese and Arab astronomers, and may have been the brightest SN in history, being the result of a Type Ia SN exploding in an approximately uniform medium and B-field. The X-ray non-thermal emission observed from its rims implies synchrotron radiation from electrons with energies of up to ~ 100 TeV. The bipolar VHE morphology is strongly correlated with that seen in X-rays, pointing to a scenario where particles are being accelerated in the shocks within the very thin rims indicated by the X-ray filaments. Either a leptonic inverse Compton scenario, or a mixed leptonic / hadronic scenario, can adequately explain the multi-wavelength observations.[11]

Pulsar Wind Nebula: HESS J1825-137

Pulsar wind nebulae (PWN) represent the largest VHE source class. A particularly interesting example is that of HESS J1825-137, first detected in the H.E.S.S. GPS.[18,20] This source is offset from the pulsar PSR J1826-1334 that is plausibly powering the nebula, probably due to the PWN's expansion in an inhomogeneous ambient medium. Spatially-resolved spectra for the first time showed an energy-dependent morphology in VHE gamma rays, exhibiting a softening in spectral index with distance from the source centre, something quite common in X-ray observations of PWN. This leads to a decrease in source size with increasing gamma-ray energy. The changing morphology probably indicates cooling of energetic particles via radiation losses as they propagate out from the pulsar termination shock, although energy-dependent convection or diffusion as well as time-dependent injection of particles may also contribute to the spectral variation.

Starburst Galaxy: NGC 253

The detection of the starburst galaxy NGC 253 represented the first non-AGN extragalactic object detected in VHE gamma rays, and it is also among the faintest sources detected thus far ($\sim 0.3\%$ of the Crab Nebula's flux). NGC 253 has a highly increased rate of massive star formation and supernovae in its nucleus, and the supernova shocks are believed to accelerate CRs up to 10^{15} eV. Given the presence of these energetic CRs, as well as dense, hot gas that manifests itself in the X-ray waveband and acts as target material, gamma-ray emission has been expected to be visible even if the source is at a few Mpc, motivating its being a target for dedicated observations. The inferred central CR density is about three orders of magnitude larger than in the centre of the Milky Way.[9]

[‡] More information on source numbers and categories is available at http://tevcat.uchicago.edu/

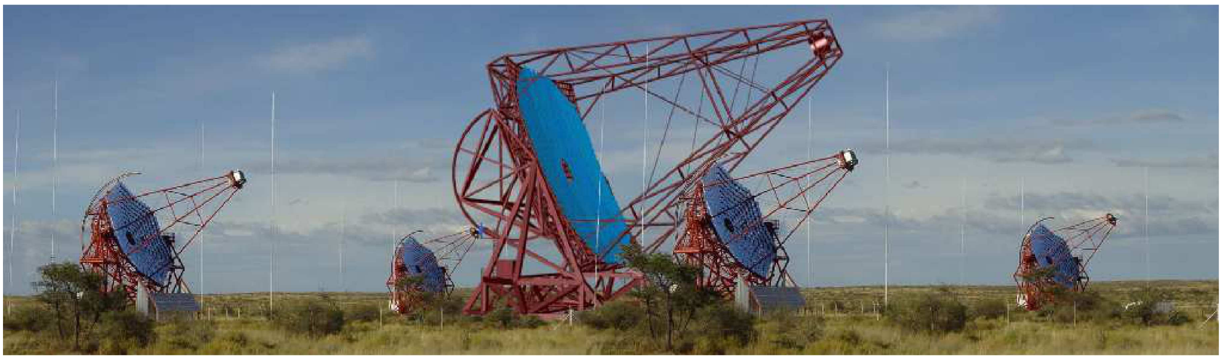

Figure 1: An artist's conception of H.E.S.S. Phase II.[70]

Dark Matter Constraints

Indirect searches for dark matter through the detection of its annihilation products is an important way of contributing to the ongoing quest for improved understanding of the properties of dark matter. Constraints on the velocity-weighted annihilation cross-section of dark matter particles have been derived in the absence of TeV excesses using several source classes, including intermediate-mass black holes,[24] the Sagittarius dwarf spheroidal galaxy,[25] the Canis Major overdensity (which may be a dwarf galaxy),[28] the globular clusters NGC 6388 and M15,[6] the Sculptor and Carina dwarf spheroidal galaxies,[8] and the Galactic Centre Halo.[7]

H.E.S.S. Phase II

In order to lower the energy detection threshold of H.E.S.S., and thereby enlarge its energy range, as well as improve sensitivity around 100 GeV, a single 28-m telescope (with a mirror area of $\sim$ 600 m^2) is being installed in the centre of the current layout (Fig. 1), and will be operated in conjunction with the four existing telescopes. This important improvement will provide complementarity for existing northern hemisphere gamma-ray experiments such as the *Very Energetic Radiation Imaging Telescope Array System* (VERITAS) and the *Major Atmospheric Gamma-Ray Imaging Cherenkov* (MAGIC), as well as temporal and energy overlap and cross-calibration for the space-based *Fermi Large Area Telescope* (LAT).[70] The relatively smaller pixel size of 0.07° (compared to 0.16° of Phase I) of the 2 048 photomultiplier tubes,[67] and FoV[41] of $\sim$ 3.2° (vs. 5°) will improve the angular resolution. These enhancements will allow probing of the many unassociated TeV sources to help pin down their characteristics, constrain pulsar spectral shapes, aid in dark matter search capability, enable observation of more distant active galaxies, and allow measurement of variability of, for example, AGN and binaries on shorter timescales.[60]

The Cherenkov Telescope Array (CTA)

While current gamma-ray observatories have enjoyed enormous success, several open questions remain. Some key object classes are still elusive, e.g. galaxy clusters as cosmological storehouses of CRs, VHE emission from gamma-ray bursts (GRBs), and detection of dark matter annihilation signatures. In addition, some key mechanisms remain to be understood, e.g., whether supernovae provide sufficient peak energy and energy output to be regarded as sources of CRs, the escape of CRs from accelerators and their propagation, and energy conversion in pulsars (W. Hoffman 2011, private communication). These puzzling unknowns underline the need for increased experimental capability, which will be afforded by the CTA. The CTA Collaboration already comprises over 700 participants from 25 countries, including almost all European countries, the United States (groups formerly involved in the *Advanced Gamma-ray Imaging System* (AGIS) project, now called the CTA-US group), Brazil, Argentina, India, Japan, South Africa and Namibia. Such a global effort will be the framework that encapsulates the future endeavours, discoveries, and progress of gamma-ray astronomy.

Instrumentation

The CTA design study[42] lists five general aims for this next-generation gamma-ray experiment: (i) an order-of-magnitude increase in sensitivity, i.e. at the milliCrab level (Fig. 2), enabling deep observations at $\sim$ 1 TeV; (ii) a significant increase in detection area, and thus detection rates, which will be crucial for observations of transient phenomena and studies at the highest energies; (iii) an increased angular resolution (factor $\sim$ 5 improvement over current systems) resulting in resolving ability for the morphology of extended sources; (iv) a uniform energy coverage in the range of tens of GeV to $>$ 100 TeV; and (v) an enhanced sky survey capability, monitoring capability and flexibility of operation. For a clear view of the full sky there will be two CTA sites: the main site in the southern hemisphere, which will focus on the central region of our Galaxy, and the northern-hemisphere site, which will primarily study AGN as well as the formation and evolution of galaxies and stars.

One promising configuration for the CTA involves three telescope types, distributed over $\sim$ 3 km^2 on the ground: four 24-metre telescopes with a 5° FoV and 0.09° pixels, 23 12-metre telescopes with an 8° FoV and 0.18° pixels, and 32 7-metre telescopes with a 10° FoV and 0.25° pixels. Such a configuration, with a projected construction cost of 80 million Euros, conforms to the CTA design goals and will yield a factor 10 increase in sensitivity over most of the required energy range. The anticipated cost of construction and site infrastructure of CTA-South and CTA-North is 100 million Euros and 50 million Euros respectively, with running costs projected at $\sim 10\%$ of the total investment.

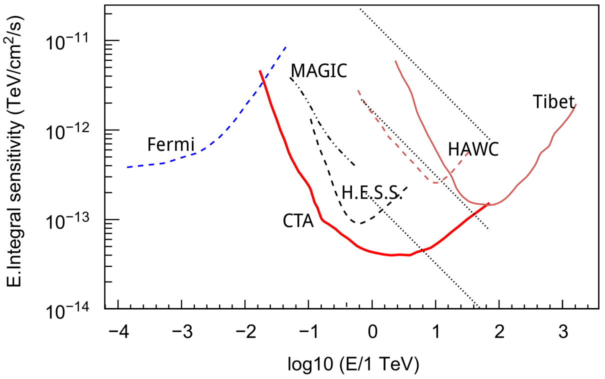

Figure 2: CTA sensitivity, compared to that of other experiments.[47] The dashed lines indicate 100%, 10%, and 1% of the Crab Nebula's integrated flux (from top to bottom).

Scientific Aims

The scientific drivers for CTA may be summarised in three main points:[42] (i) the origin of CRs and their role in the Universe (dealing with sources such as pulsars, PWN, SNRs, gamma-ray binaries, star-forming regions, and starburst galaxies); (ii) probing the nature and variety of particle acceleration around SMBHs (encompassing blazars, radio galaxies, and other classes of AGN, as well as the EBL, galaxy clusters, and GRBs); (iii) searching for the ultimate nature of matter and physics beyond the Standard Model (searches for the elusive dark matter, tests of Lorentz invariance, and any other challenging observational signatures).

Timeline

A number of phases are envisaged over the CTA's lifetime, including a design study phase, prototyping and preparatory phase, construction phase, and operation phase.[42] Fortunately the hardware needed for the CTA is based on mature technology which has demonstrated capability in the current generation of gamma-ray telescopes. The CTA Preparatory Phase (with a budget of $\sim$ 10 million Euros) commenced in October 2010, and is expected to last for $\sim$ three years. The aim of this phase is to investigate the science which is possible with the CTA on the one hand, and the administrative and technical aspects of the telescope construction and operation on the other.[*] The Project Office is located at the Landessternwarte in Heidelberg and coordinates various work packages, including those relating to administration and governance, site aspects, quality control, data and public outreach, as well as technical packages relating to the telescope design. If sufficient funding is secured, construction and deployment will take place during 2013–2018, with partial operation starting in $\sim$ 2016.

The Southern African CTA Site Proposal

South Africa, Namibia, Argentina, and Brazil have expressed interest in hosting CTA-South (while possible northern sites include the Canary Islands, India, and North America). Southern Africa possesses an extremely low night sky background,[39] making it attractive for astronomical endeavours. Furthermore, an early automated search for potential CTA sites revealed that only regions in South Africa, Namibia, and South America (and possibly Australia) satisfy the criteria for hosting CTA South (see Table 1).[35]

South Africa has a single viable site that fulfills the requirements. This is located south of Sutherland, close to the location of SALT, the largest optical telescope in the southern hemisphere. While this site provides good infrastructure and easy access, only about 47% of the nights are of photometric quality usable for gamma-ray observations,[56] while the minimum requirement is 1000 h of moonless observation time ($\sim$ 60%). The inferred fraction of photometric nights for the Sutherland site is close to the results of a study conducted in the 1970s,[48] which found 51%. Furthermore, the site is about 1500 m.a.s.l., which barely passes the minimum height requirement.

In Namiba, there are sites with higher elevation and more cloudless nights. The current H.E.S.S. site is 1840 m.a.s.l., has 64% cloudless nights, very low night sky background levels, and is only 100 km from Windhoek. Another site, Kuibis, situated between Keetmanshoop and Luderiz, i.e.south of the H.E.S.S. site, is 1640 m.a.s.l., boasting clear skies 73% of the year. It is also close to the B4 national highway, a railway line, power line, optical fibre line, and a national airport and harbour. These Namibian sites also have excellent properties in terms of snow load, wind speed, and seismic stability.

The South African government has invested heavily in multiwavelength astronomy, specifically in the SALT and MeerKAT / SKA projects. Passing legislation to protect the geographic advantage of regions in the Northern Cape from light pollution demonstrates its continued commitment to developing astronomy in the African context. In view of the extraordinary potential of a project such as CTA for economic, social and educational upliftment in Southern Africa, the government is supporting a Southern African CTA site proposal with a site located in Namibia.

Examples of Multiwavelength Synergies

Unprecedented opportunities exist nowadays to study astrophysical sources within a multiwavelength context using a complementary approach for source discovery, as well as disentangling details of particle injection, acceleration, transport, and radiation within these sources. Below are a few examples.

Pulsars

The high-energy (HE) astrophysics domain was revolutionised by the launch of the *Fermi* Large Area Telescope (LAT) on 11 June 2008.[31] The second *Fermi* catalogue is in production and contains nearly 1 900 gamma-ray sources.[37,68] Among the numerous discoveries are almost 100 gamma-ray pulsars.[4,66] Almost a third of these have been found using blind periodicity searches in the gamma-ray data at *a priori* source positions.[1,65] Follow-up observations in the radio band found pulsations from only three of these,[2,38] and radio upper limits for 23 more.[66] This means that the bulk of these gamma-ray-selected pulsars is still radio-faint, either due to beaming effects, or intrinsically weak radio emission properties. Deep searches with (future) radio telescopes such as MeerKAT and SKA in the *Fermi* LAT radio-faint pulsar error boxes may reveal weak radio emission and thus lead to the discovery of more radio pulsars. This will impact pulsar population modelling since one important prediction of such models is the fraction of radio-quiet (Geminga-like) pulsars.[49]

---

[*] www.cta-observatory.org/

Table 1: Criteria for the CTA Site

Size	South: $\geq 10\,\mathrm{km}^2$; North: $\geq 1\,\mathrm{km}^2$
Flatness	Height variation $\Delta h < 150$ m
Cloud Coverage	$> 70\%$ of nights good for observation
Altitude	1500 m − 3800 m
Night Sky Background	Better than U: 21.55 mag/arcsec^2 B: 22.25 mag/arcsec^2 V: 21.25 mag/arcsec^2
Wind Speed	$< 50\,\mathrm{km/h}$ for 80% of observable time, $< 200\,\mathrm{km/h}$ safety limit
Additional Requirements	Snow load Seismic activity Medical rescue Some level of infrastructure development Local support

A number of millisecond pulsars (MSPs) have now been found by observing non-variable, unassociated *Fermi* sources at high latitudes with radio telescopes, and searching for pulsed radio signals.[40,55,62] This is in contrast to the traditional method where gamma-ray data in the direction of known radio pulsars is searched for using the radio ephemeris. These discoveries suggest a new mode of discovery, and future radio follow-up of *Fermi* unidentified bright sources with pulsar-like spectra may lead to many more (millisecond) pulsar discoveries.

The detection of many gamma-ray pulsars for the first time affords the opportunity for true multiwavelength modelling. One example is being able to constrain the pulsar geometry (inclination and observer angles α and ζ) using complementary approaches: radio light curve as well as polarisation swing data and application of the rotating vector model[61] provide constraints[73] on α and $\beta = \zeta - \alpha$, while geometric gamma-ray and radio light curve modelling provide additional constraints[64,69] on α and ζ. Further constraints on ζ may be derived using X-ray PWN data.[57]

Previous predictions of low inverse Compton VHE components for certain pulsar parameters,[36,52] as well as HE spectral fits with cutoffs around a few GeV for all of the current *Fermi* pulsars,[4] impacted negatively on expectations for VHE emission from pulsars. However, a very recent detection of the Crab pulsar at several hundred GeV by the VERITAS Collaboration[59] now suggests that pulsar science may indeed be possible using ground-based Cherenkov telescopes. The lower energy threshold of CTA will greatly aid in constraining the spectral shapes and therefore magnetospheric properties such as the electric field and radius of curvature of particle orbits.

Active Galactic Nuclei

The active galaxy PKS 2155-304 was among the first sources detected by H.E.S.S.,[14] and an extreme gamma-ray outburst at ten times the usual flux level was reported subsequently.[22] This BL Lac object has furthermore been observed in follow-up multiwavelength campaigns. The first of these involved H.E.S.S., the *Rossi X-ray Timing Explorer* (RXTE) satellite, the *Robotic Optical Transient Search Experiment* (ROTSE), and the *Nançay Decimetric Radio Telescope* (NRT). During this campaign, the object appeared to be in a quiescent state, exhibiting flux variability in all wavebands, flux-dependent spectral changes in the X-rays, and also a transient X-ray event with a 1500-second timescale.[17] During a second campaign, *Fermi* LAT provided MeV to GeV coverage, while the *ATOM* telescope and RXTE and *Swift* observatories provided concurrent optical and X-ray observations. This time, the object was in a low X-ray and VHE state, but the optical flux was relatively high.[29] There was a clear correlation of optical and VHE fluxes (hinting at a common parent-particle population), and a possible correlation between the X-ray flux and HE spectral index, but none between the X-ray and VHE components (in contrast to what is seen in many other blazars).

This example indicates how vital simultaneous observations in various energy regimes are to help constrain the source properties. In particular, an optical telescope such as SALT, with its superior sensitivity, allows probing of polarisation variations with time. This will help to distinguish between multiple active emission sites, and constrain their structure, location, geometries, environments, evolution, local magnetic field properties, and the particle acceleration and cooling processes, as well as guide construction of future multizone models.[32] In addition, SALT spectroscopy and images will allow identification of new high-redshift AGN associated with high-latitude unidentified, variable *Fermi* sources.

Astrophysical Lepton and Hadron Colliders

SNRs have long been thought to be accelerators of hadronic CRs.[46] However, electrons are also believed to be accelerated to very high energies in these systems. Gamma-ray signals from such SNRs may therefore originate either from hadronic or leptonic CRs interacting with ambient matter, soft radiation fields, or electromagnetic fields – or a combination of both – and it is difficult to discriminate between the two scenarios.[12,16,44] One example is the H.E.S.S. detection of VHE flux in the direction of the old W28 SNR, known to be interacting with surrounding molecular clouds along its north and north-eastern boundaries. The gamma-ray flux revealed a partial correlation with the radio emission, but a good correlation with NANTEN $^{12}\mathrm{CO}(J = 1-0)$ data.[26] The gamma-ray flux therefore follows the molecular gas structure, probably pointing, in this case to the interaction of hadronic CRs with the target material.

Fermi has also begun to contribute to the debate on the relative contribution of hadronic vs. leptonic parent populations to the observed gamma-ray signals from several SNRs.[3,5] However, *Fermi* source identification and characterization suffer significantly from the contributions of the diffuse, structured Galactic gamma-ray background that traces molecular clouds near the Galactic Plane, while this diffuse background is very faint at TeV (H.E.S.S. and CTA) energies. MeerKAT's survey potential will discover new resolved sources of energetic particles (e.g. SNRs and colliding winds), so that a combination of MeerKAT, H.E.S.S. / CTA, and CO observations should resolve many more hadron colliders in the Galactic Plane, thereby constraining the origin of VHE signals from several more sources.

Conclusion

A White Paper reviewing the status and future of ground-based gamma-ray astronomy[34] came to several important conclusions. Among other findings, it suggested that advances in instrumentation and analysis techniques make gamma-ray astronomy one of the most exciting new windows on the Universe, with many new sources presently being discovered. Indeed, the successful maturing of gamma-ray astronomy, building on pioneering experiments of the past, has now led to the detection of $\sim$ 100 TeV sources, $\sim$ 2000 GeV sources, and the prospects of H.E.S.S. Phase II, and the next-generation ground-based observatory CTA, will potentially increase the first number to $\sim$ 1000 TeV sources. The main scientific drivers have been to study particle acceleration and propagation, finding dark matter (together with accelerator experiments), studying SMBHs and EBL, and cosmology. In this sense, gamma-ray astronomy is very complementary to observatories operating in other wavebands, including neutrino and gravitational experiments. Importantly, this paper also points out that since there is no follow-up space-based experiment planned for *Fermi* LAT (which has limited angular and energy resolution, and a relatively small collection area), the construction of a new-generation ground-based gamma-ray observatory operated by an international collaboration is crucial. Such an observatory will lead to the development of new technology, human capacity building, and a greater level of appreciation of science by the public, in addition to making the most of the unprecedented opportunities that now exist to learn more about the violent, extreme, non-thermal Universe, following a collaborative approach with experiments operating at lower energies.

Acknowledgments

The author wishes to thank Werner Hoffman, Paulus Krüger, Johan van der Walt, and Okkie de Jager for invaluable discussions on various topics related to this paper. He also acknowledges the support of the South African National Research Foundation.

References

[1] Abdo, A.A. *et al.* 2009, *Science*, 325, 840.

[2] Abdo, A.A. *et al.* 2009, *Astrophys. J.*, 700, 1059.

[3] Abdo, A.A. *et al.* 2010, *Science*, 327, 1103.

[4] Abdo, A.A. *et al.* 2010, *Astrophys. J. Suppl.*, 187, 460.

[5] Abdo, A.A. *et al.* 2011, *Astrophys. J.*, 734, 28.

[6] Abramowski, A. *et al.* 2011, *Astrophys. J.*, 735, 12.

[7] Abramowski, A. *et al.* 2011, *Phys. Rev. Lett.*, 106, 161301.

[8] Abramowski, A. *et al.* 2011, *Astroparticle Phys.*, 34, 608.

[9] Acero, F. *et al.* 2009, *Science*, 326, 1080.

[10] Acero, F. *et al.* 2010, *Mon. Not. R. astr. Soc.*, 402, 1877.

[11] Acero, F. *et al.* 2010, *Astron. Astrophys.*, 516, A62.

[12] Aharonian, F.A. *et al.* 2004, *Nature*, 432, 75.

[13] Aharonian, F.A. *et al.* 2004, *Astron. Astrophys.*, 425, L13.

[14] Aharonian, F.A. *et al.* 2005, *Astron. Astrophys.*, 430, 865.

[15] Aharonian, F.A. *et al.* 2005, *Astron. Astrophys.*, 432, L25.

[16] Aharonian, F.A. *et al.* 2005, *Astron. Astrophys.*, 437, L7.

[17] Aharonian, F.A. *et al.* 2005, *Astron. Astrophys.*, 442, 895.

[18] Aharonian, F.A. *et al.* 2005, *Astron. Astrophys.*, 442, L25.

[19] Aharonian, F.A. *et al.* 2006, *Nature*, 439, 695.

[20] Aharonian, F.A. *et al.* 2006, *Astron. Astrophys.*, 460, 365.

[21] Aharonian, F.A. *et al.* 2006, *Astrophys. J.*, 636, 777.

[22] Aharonian, F.A. *et al.* 2007, *Astrophys. J.*, 664, L71.

[23] Aharonian, F.A. *et al.* 2008, *Astron. Astrophys.*, 457, 899.

[24] Aharonian, F.A. *et al.* 2008, *Phys. Rev. Lett.*, 78, 072008.

[25] Aharonian, F.A. *et al.* 2008, *Astroparticle Phys.*, 29, 55.

[26] Aharonian, F.A. *et al.* 2008, *Astron. Astrophys.*, 481, 401.

[27] Aharonian, F.A. *et al.* 2008, *Astron. Astrophys.*, 492, L25.

[28] Aharonian, F.A. *et al.* 2009, *Astrophys. J.*, 691, 175.

[29] Aharonian, F.A. *et al.* 2009, *Astrophys. J.*, 696, L150.

[30] Aharonian, F.A. *et al.* 2009, *Astron. Astrophys.*, 503, 817.

[31] Atwood, W.B. *et al.* 2009, *Astrophys. J.*, 697, 1071.

[32] Barres de Almeida, U., Ward, M.J., Dominici, T.P., Abraham, Z., Franco, G.A.P., Daniel, M.K., Chadwick, P.M., Boisson, C. 2010, *Mon. Not. R. astr. Soc.*, 408, 1778.

[33] Benbow, W. 2005, in: F.A. Aharonian, H.J. Völk, & D. Horns (eds.), *Proc. 2nd International Symposium on High-Energy Gamma-Ray Astronomy, AIP Conf. Ser.*, 745, 611.

[34] Buckley, J. *et al.* 2008, arXiv:0810.0444.

[35] Bulik, T. *et al.* 2009, *Report written for CTA SITE Package*.

[36] Bulik, T., Rudak, B., Dyks, J. 2000, *Mon. Not. R. astr. Soc.*, 317, 97.

[37] Burnett, T.H. 2011, *Proc. 3rd Fermi Symposium*, in press.

[38] Camilo, F. *et al.* 2009, *Astrophys. J.*, 705, 1.

[39] Cinzano, P., Falchi, F., Elvidge, C.D. 2001, *Mon. Not. R. astr. Soc.*, 328, 689.

[40] Cognard, I. *et al.* 2011, *Astrophys. J.*, 732, 47.

[41] Cornils, R, Bernlöhr, K., Heinzelmann, G., Hofmann, W., Panter, M. 2005, in: B.S. Acharya, S. Gupta, P. Jagadeesan, A. Jain, S. Karthikeyan, S. Morris, & S. Tonwar (eds.), *Proc. 29th ICRC, Pune, India*, 5, 171.

[42] CTA Consortium 2010, *Design Concepts for the Cherenkov Telescope Array CTA* (arXiv:1008.3703).

[43] Djannati-Ataï, A. 2009, *Nucl. Instr. & Meth. in Phys. Res. A*, 602, 28.

[44] Gabici, S. 2008, *Proc. XXI European Cosmic Ray Symp.* (arXiv:0811.0836).

[45] Gast, H. 2011, *Proc. 32nd ICRC*, in press.

[46] Ginzburg, V.L., Syrovatskii, S.I. 1964, *The Origin of Cosmic Rays*, New York: Macmillan.

[47] Glicenstein, J.-F. 2011, *Nucl. Instr. & Meth. in Phys. Res. A*, 639, 46.

[48] Harding, G. 1974, *SAAO Circulars*, 1, 31.

[49] Harding, A.K., Grenier, I.A., Gonthier, P.L. 2007, *Astrophys. Space Science*, 309, 221.

[50] Hinton, J.A. 2004, *New Astron. Rev.*, 48, 331.

[51] Hinton, J.A., Hofmann, W. 2009, *Annual Review of Astron. & Astrophys.*, 47, 523.

[52] Hirotani, K. 2007, *Astrophys. J.*, 662, 1173.

[53] Hofmann, W. 2005, in: B. Degrange, & G. Fontaine (eds.), *Towards a Network of Atmospheric Cherenkov Detectors VII, Palaiseau, France*, p. 43.

[54] Horns, D. 2008, in: S. Röser (ed.), *Rev. in Mod. Astron.*, 20, 167.

[55] Keith, M.J. *et al.* 2011, *Mon. Not. R. astr. Soc.*, 414, 1292.

[56] Krüger, P.P. & Van der Walt, D.J. 2011, Southern African CTA Site Proposal, (arXiv:1202.4747).

[57] Ng, C.-Y., Romani, R.W. 2008, *Astrophys. J.*, 673, 411.

[58] Ong, R.A. 1998, *Phys. Rep.*, 305, 93.

[59] Otte, A.N. *et al.* 2011, *Proc. 3rd Fermi Symposium*, (arXiv:1111.6610v1).

[60] Punch, M. *et al.* 2005, in: B. Degrange, & G. Fontaine (eds.), *Towards a Network of Atmospheric Cherenkov Detectors VII, Palaiseau, France*, p. 379.

[61] Radhakrishnan, V., Cooke, D. J. 1969, *Astrophys. J. Letters*, 3, 225.

[62] Ransom, S.M. *et al.* 2011, *Astrophys. J. Letters*, 727, L16.

[63] Renaud, M. 2009, *Proc. 44th Rencontres de Moriond* (arXiv:0905.1287).

[64] Romani, R.W., Watters, K.P. 2010, *Astrophys. J.*, 714, 810.

[65] Saz Parkinson, P.M. *et al.* 2010, *Astrophys. J.*, 725, 571.

[66] Smith, D.A. 2011, *Proc. 3rd Fermi Symposium*, in press.

[67] Tluczykont, M., Fontaine, G., Ouchrif, M., Prévotet, J.-C., Verdier, F. 2005, in: B. Degrange, & G. Fontaine (eds.), *Towards a Network of Atmospheric Cherenkov Detectors VII, Palaiseau, France*, p. 509.

[68] Thompson, D.J. 2011, *Proc. 3rd Fermi Symposium*, in press.

[69] Venter, C., Harding, A.K., Guillemot, L. 2009, *Astrophys. J.*, 707, 800.

[70] Vincent, P. *et al.* 2005, in: B.S. Acharya, S. Gupta, P. Jagadeesan, A. Jain, S. Karthikeyan, S. Morris, & S. Tonwar (eds.), *Proc. 29th ICRC, Pune, India*, 5, 163.

[71] Weekes, T.C. *et al.* 1989, *Astrophys. J.*, 342, 379.

[72] Weekes, T.C. 2008, in: F.A. Aharonian, W. Hofmann, & F. Rieger, (eds.), *Proc. 4th International Symposium on High-Energy Gamma-Ray Astronomy*, *AIP Conf. Ser.*, 1085, 3.

[73] Weltevrede, P. *et al.* 2010, *Astrophys. J.*, 708, 1426.