2002BASI...30...17F

Bull. Astr. Soc. India (2002) **30**, 17–23

VHE Gamma-ray Astronomy: Present Status and Future Challenges

J. P. Finley

Dept. of Physics, Purdue University
West Lafayette, IN, 47907, USA

Abstract.
This paper will report on the status of VHE gamma-ray astronomy at the start of the new millennium. The decade of the 90's saw rapid development of the field and many new detectors and proposed facilities are discussed. The growth of the field in the new millennium will continue and the catalogue of TeV sources will increase by at least an order of magnitude. While many advances are expected some "thorny" problems, which have been around for quite a while, may still prove to be a challenge in the future.

Key words: Gamma rays, Ground based gamma-ray astronomy.

1. Introduction

The decade of the 90's was a "golden age" in the field of very high energy (VHE) gamma-ray astronomy. The decade saw the establishment of the Crab Nebula (Weekes 1989) as the standard candle of the field with the development of the Imaging Atmospheric Cherenkov Technique (IACT) by the Whipple collaboration. This initial signal, though meager at the time ($\sim 6\sigma$ in 60 hours of observation), provided the test bed for subsequent improvements in detectors and analysis techniques. The fruit of that labor was not long in coming. A new class of active galactic nuclei (AGN), the TeV Blazars Mrk 421 and Mrk 501, were soon detected (Punch et al. 1992, Quinn et al. 1996) and rapid variability (Gaidos et al. 1996) challenged the current ideas regarding the nature of the accelerator in these objects. The solution to the long standing mystery of the origin of the cosmic rays was hinted at with the detections of diffuse emission from the supernova remnants SN 1006 (Tanimori et al. 1998) and Cassieopia A (Aharonian et al. 2001). Further developments included demonstration of the utility of stereoscopic imaging by the HEGRA collaboration (Kohnle et al. 1996) and the gains that can be realized by utilizing a fine pixel camera by the CAT collaboration (Barrau et al. 1998). A listing of all the currently operating Imaging ACT's is compiled in Table 1.

TABLE 1: Imaging Air Cherenkov Telescopes Circa 2000

Collaboration	Location	Telescopes (Aperture)	Camera (Pixels)	Threshold (TeV)
Whipple *USA–Ireland–UK*	Arizona	10m	490	0.2
HEGRA *Germany–Spain–Armenia*	La Palma	6×3m	271	0.5
CAT *France*	Pyren'ees	4.5m	600	0.25
CANGAROO–II *Japan–Australia*	Woomera	10m	552	0.5
TACTIC *India*	Mt. Abu	4×3.5m	349	0.6
SHALON *Russia*	Tien Shen	4m	244	1.0
Crimea *Ukraine*	Crimea	6×2.4m	37	1.0
7TA *Japan*	Utah	7×2m	256	0.5

In addition to the imaging technique other avenues have also been explored and developed during the decade including non–imaging arrays such as the Pachmarhi array (Bhat et al. 2001) that use wave front sampling to reconstruct shower directions, solar arrays such as STACEE (Chantell et al. 1998), Celeste (Quebert et al. 1995), and Solar–2 (Tümer et al. 1999) that exploit the large mirror area available to reach low thresholds, and large non–Cherenkov facilities such as Milagro (Sinnis et al. 1995) and the Tibet HD array (Amenomori et al. 1997). A compilation of these instruments can be found in Tables 2, 3, and 4 below.

TABLE 2: Air Cherenkov Solar Array Telescopes Circa 2000

Collaboration	Location	Heliostats Current(Future)	Threshold (GeV)
STACEE *USA–Canada*	New Mexico	32(48)	180
CELESTE *France*	Themis	40(54)	40–60
Solar–2 *USA*	California	32(64)	20
GRAAL *Germany–Spain*	Almeria	4(18)	200

TABLE 3: Non–Imaging Air Cherenkov Telescopes Circa 2000

Collaboration	Location	Telescopes (Type)	Threshold (TeV)
PACT *India*	India	24 *Lateral Array*	0.9
Beijing *China*	China	2 *Double*	1.0

TABLE 4: Non–Atmospheric Cherenkov Telescopes Circa 2000

Collaboration	Location	Type	Threshold (TeV)
Milagro *USA*	New Mexico	Water Cherenkov	0.5
Tibet HD *China–Japan*	Tibet	Scintillator Array	3.0

This persistent and diligent work has led to a VHE catalogue which now contains 13 sources, 7 galactic and 6 extragalactic, which are given in Table 5 and Table 6 below.

TABLE 5: Galactic VHE Sources Circa 2000

Source	Type	Discovery	EGRET source
Crab Nebula	Plerion	1989	X
PSR B1706–44	Plerion?	1995	–
Vela	Plerion?	1997	–
SN1006	Shell SNR	1997	–
RX J1713.7–3946	Shell SNR	1999	–
Cassiopeia A	Shell SNR	1999	–
Centaurus X–3	X-ray binary	1999	X

TABLE 6: Extragalactic VHE Sources Circa 2000

Source	Type	z	Discovery	EGRET source
Markarian 421	XBL	0.031	1992	X
Markarian 501	XBL	0.034	1995	X
1ES 2344+514	XBL	0.044	1997	–
1ES 1959+650	XBL	0.048	1999	–
PKS 2155–304	XBL	0.116	1999	–
3C66A	RBL	0.44	1998	X

2. VHE Gamma-ray Astronomy in the New Millennium

The next step forward in VHE gamma-ray astronomy requires new facilities that fully incorporate the lessons learned during the decade of the 90's. Substantial progress can be made by extending the energy coverage of the instruments while simultaneously preserving good energy resolution and increasing the flux sensitivity by improved angular resolution and better gamma/hadron discrimination. While ideally one would like to have a facility which incorporates all the advances in a practical sense some tradeoffs must be made. The lowest energy threshold requires large mirror areas and this is the approach which the solar array telescopes are pursuing (see Table 2 above) and a newly proposed German–Spanish 17m telescope utilizing the IACT (MAGIC) (Barrio et al. 1998). These instruments will achieve energy thresholds of 20–30 GeV and effectively close the gap from 20 – 200 GeV between current VHE ground based instruments and space based detectors. This gap will ultimately be covered by the next generation space based high energy gamma-ray telescope GLAST (Gehrels & Michelson 1999) which is the follow-up to the extremely successful EGRET of the 90's. At energies of tens of TeV and above large particle detector arrays at high mountain altitudes or air cherenkov telescopes operating at large zenith angles are necessary. A novel approach is the newly commissioned MILAGRO water cherenkov detector which will have a large field of view (virtually full sky) with a 24 hour duty cycle and good sensitivity for bursts and transients (Sinnis et al. 1995). In the 50 GeV to 10 TeV band a concentrated effort has been launched worldwide which incorporates arrays of telescopes with high resolution cameras to take full advantage of stereoscopic imaging and good shower reconstruction. The 3 efforts are VERITAS, a USA–UK–Ireland collaboration (Catanese & Weekes 1999), HESS, a German–Spanish collaboration (Hofmann 1997), and CANGAROO III, a Japanese–Australian effort. The properties of these facilities are given in Table 7 below.

2.1 VERITAS

The VERITAS array is a 7 telescope 10m aperture system based upon the original Whipple collaboration 10m telescope in a hexagonal arrangement with 80 meters separating the individual telescopes. The individual telescopes of the array will be a Davies–Cotton design with an *f*-number of 1.2 (i.e. a focal length of 12 meters). The angular size of the individual pixels of the cameras will be $0^\circ.15$ and the total of 499 close packed photomultipliers will yield a field–of–view of $3^\circ.6$ diameter. The signals of the pixels will be read out by a 500 MHz flash ADC system and will be equivalent to having an oscilloscope attached to each channel. The array will be located in southern Arizona at an altitude of 1.4 km above mean sea level. The array was optimized to give good sensitivity over the bandpass from 100 GeV to 10 TeV with good response at 50 GeV. The main scientific motivation behind the optimization of the system was systematic studies of AGN, SNRs, and gamma-ray bursts with the ability to run multiple programs simultaneously. First light of the entire VERITAS array is scheduled for 2005. A top priority of the collaboration is performance of a survey of the first quadrant of the Galactic plane. See Catanese & Weekes (1999) for an overview of the VERITAS facility.

2.2 HESS

The HESS collaboration is a joint German–French effort which is comprised of former members of both the HEGRA and CAT collaborations. The system is an array of initially 4 12m telescopes arranged in a square configuration with 120 meters separating the individual telescopes. The collaboration intends an expansion to 16 telescopes in the future. The individual telescopes have an *f*-number of 1.25 (i.e. a focal length of 15 meters) and utilize a Davies–Cotton arrangement. The angular pixel size of the individual 800 pixel cameras is $0^\circ.15$ and the total field–of–view is $\sim 5^\circ$ diameter. The array will be located in Namibia at an altitude of 1.8 km above mean sea level. The array optimization was driven by the necessities of observing SNRs and the sensitivity is very similar to VERITAS with a bandpass from 50 GeV to 50 TeV. First light of the HESS array is scheduled for 2002 with science results expected in 2003. A detailed treatment of the HESS array can be found in Hofmann (1997).

2.3 CANGAROO III

The CANGAROO III collaboration is a joint effort between Japan and Australia which is a continuation of the successful CANGAROO group. The system will be an array of 4 10m aperture telescopes in a square arrangement of 120 meters spacing. Unlike both VERITAS and HESS the mirror is a parabolic figure with an *f*-number of 0.8 (i.e. a focal length of 8 meters). The 512 pixel cameras will have individual pixels with an angular size of $0^\circ.24$ yielding a fairly large field–of view. The array will be located in Woomera at sea level. The sensitivity is also similar to both VERITAS and HESS with a bandpass of $\sim$ 100 GeV to 10 TeV. The array is scheduled for first light in 2003.

3. Future Challenges

While the coming decade will see the field of VHE gamma-ray astronomy grow rapidly, with perhaps a few surprises in store, there are still some nagging challenges which must be addressed. A large motivation of the field and one of the primary reasons for its inception was the chance to solve the long standing mystery of the cosmic rays. The detection of SNRs by both the HEGRA collaboration and the CANGAROO collaboration seem to indicate that the solution to the puzzle may be in hand. However, X-ray data indicate the presence of very high energy electrons which are possibly inverse compton scattering cosmic microwave background photons (Reynolds 1996, Mastichiadis & De Jager 1996) to produce the observed signal. In this scenario no hadronic component is necessary and essentially confuses the issue of the cosmic ray origin. Detailed maps are required of the emission from SNR shells to sort out the origin of the emission but the smoking gun, detection of the pion bump from $\pi^0 \rightarrow \gamma\gamma$, may end up being the purview of lower energy space based detectors like GLAST.

Another nagging issue which has been around for some 30 years involves the nature of the pulsar mechanism. Despite intensive study of these rotating neutron stars over the past 35 years we can still not say with any certainty what makes a pulsar "shine".

Key to understanding the mechanism, in particular the nature of the accelerator, is to measure the cutoff of the high energy emission which must lie between ~ 20 GeV and ~ 200 GeV. The 2 most accepted models of pulsar emission at high energies, the polar cap models (Daugherty & Harding 1982) and the outer gap models (Romani 1996), can be distinguished with measurement of the pulsar cutoff. While there is some chance that the next generation arrays can accomplish this study the best chance most likely lies with the solar array instruments such as STACEE and Celeste, or later in the decade, by the space based high energy telescope of GLAST.

TABLE 7: Future VHE Observatories

	HESS	CANGAROO III	VERITAS
Collaboration	Germany–France	Japan–Australia	USA–UK–Ireland
Science	SNR	Galactic Sources	SNR, AGN, Bursts
OSS	Steel	Steel	Steel
Facets	60 cm. circular	80 cm. circular	60 cm. hexagonal
Material	Ground glass	Composite	Float Glass
Supplier	Czech/Armenia	Japan	USA
PMTs	Photonis	Hamamatsu	TBD
# of pixels	4×800	4×512	7×499
Pixel Size	0.15°	0.24°	0.15°
Electronics	–	–	FADC
Cabling	Coax	Coax	Coax
Location	Namibia	Woomera	Arizona
Elevation	1.8 km	Sea Level	1.4 km
# of Telescopes	4(16)	4	7
Array Pattern	Square	Square	Hexagonal
Spacing	120m	100m	80m
Design	Davies–Cotton	Parabolic	Davies–Cotton
Aperture	12m	10m	10m
Focal Length	15m	8m	12m
First Light	2002	2003	2005

4. Conclusions

Those working in the field of VHE gamma-ray astronomy are preparing for the next step forward in the maturity of the science being produced. With the low energy instruments utilizing solar arrays such as STACEE, Celeste, and Solar–2 producing data, the potential of the large ground–based arrays VERITAS, HESS, and CANGAROO–III, and the higher energy capabilities of instruments such as Tibet HD, Milagro, PACT, and TACTIC the energy band between ~ 20 GeV and 100's of TeV will be intensely explored for the first time. Catalogues of sources will increase by orders of magnitude and perhaps, with a little luck, new classes of sources will be discovered. All the hope should be tempered with the realization that the new frontier will not be easy to explore. Some long standing problems, such as the origin of the cosmic rays and the nature of the pulsar mechanism mentioned here, may be solved in the near future but perhaps by lower energy space based instrumentation. Despite that the future does indeed look bright and with any luck a conference at the dawn of the next decade will contain a rich bounty of scientific results and some heretofore unknown puzzles for the next decade of advancement.

Acknowledgements: The author would like to thank the organizers of the conference for their hospitality and assistance during the stay in Mt. Abu.

5. References

Aharonian, F., et al., 2001, A&A, 370, 112.
Amenomori, M., et al., 1997, Proc. 25th ICRC (Durban), 5, 245.
Barrau, A., et al., 1998, NIM A, 416, 278.
Barrio, J. E., et al., 1998, The Magic Telescope, design study, MPI–PhE/98–5.
Bhat, P. N., et al., 2001, *these proceedings.*
Catanese, M., & Weekes, T. C., 1999, PASP, 111, 1193.
Chantell, M. C., 1998, NIM A, 408, 468.
Daugherty, J. K., & Harding, A. K., 1982, ApJ, 252, 337.
Gaidos, J., et al., 1996, Nature, 383, 319.
Gehrels, N., & Michelson, P., 1999, APh, 11,277.
Hofmann, M., 1997, in Proc. Workshop on TeV γ–ray Astrophysics (Kruger Park, South Africa), ed. O. C. De Jager, 405.
Kohnle, A., et al., 1996, APh, 5, 119.
Mastachiadis, A., & De Jager, O. C., 1996, A&A, 311, L5.
Punch, M., et al., 1992, Nature, 358, 477.
Quebert, J., et al., 1995, in Towards a Major Atmospheric Cherenkov Detector–IV (Padova, Italy), ed. M. Cresti, 248.
Quinn, J., et al., 1996, ApJ, 456, L83.
Reynolds, S. P., 1996, ApJ, 459, L13.
Romani, R. W., 1996, ApJ, 470, 469.
Sinnis, C., et al., 1995, Nucl. Phys. B, 43, 141.
Tanimori, T., et al., 1998, ApJ, 497, L25.
Tümer, T., et al., 1999, APh, 11, 271.
Weekes, T. C., et al.,1989, ApJ, 342, 379.