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Ground-Based Gamma-Ray Detection of High Energy Galactic Sources: An Update

G. P. Rowell

Max Planck Institut für Kernphysik, D-69029 Heidelberg, Germany

Abstract. I review the present status of ground-based γ-ray astronomy, concentrating on the population of Galactic TeV sources. A number of new telescope systems are now being completed, and promise to yield exciting new discoveries, expanding rapidly the number of sources. The TeV Galactic sources today include a number of plerions, shell-type supernova remnants, an X-ray binary, and also one unidentified candidate. Their present status, and our understanding of their TeV γ-ray emission processes are summarized and some motivation driving development of the field is outlined.

1. Introduction

Ground-based γ-ray astronomy (at energies $E > 100$ GeV) has been developing rapidly in the last ten years. The advent of a number of *next-generation* instruments in 2003/2004 promises exciting new results and answers to some long-standing questions. Strongly motivating the development of new detectors and telescopes, are the questions surrounding the acceleration of particles to multi-TeV energies in many Galactic environments. It has been known for some time that various evolutionary paths following a supernova explosion can lead to the production of high-energy cosmic ray (CR) electrons and hadrons to TeV energies and above, and with them, γ-radiation as the most accessible *tracer* of this process. The main motivation driving the search for Galactic TeV sources has been concerned with the origin of these CRs. In particular, the shell-type supernova remnants (SNRs) have long-been thought responsible for the hadronic CRs up to the "knee" energy $E \sim 10^{15}$ eV. From the first convincing discovery of TeV γ-rays from the Crab plerion $\sim$ 20 years ago (Weekes et al. 1989), Galactic objects now comprise a large fraction of cataloged TeV γ-ray emitters.

In this review, I will outline the present and future developments in ground-based γ-ray astronomy, emphasizing the imaging atmospheric Čerenkov technique, and will also review the various Galactic objects identified as sources of TeV γ-rays. Some present and future scientific questions are also posed. Other reviews of the field, some including summaries of experiments using other techniques to detect TeV γ-rays are given by Aharonian (1999), Weekes (2000), Rowell (2001) and Ong (2004).

2. Ground-Based γ-ray Astronomy: The Imaging Technique

Ground-based γ-ray detection relies on the sampling of extensive air showers (EAS) through their copious Čerenkov photon yield. EAS comprise the secondary cascade particles (mostly $e^{\pm}$) generated as a primary γ-ray interactions with the Earth's atmosphere, and the Čerenkov photons carry specific information about EAS development. A major feature of the feature is the huge effective collection area $> 10^9$ cm^2 afforded by the wide area over which the Čerenkov photons are distributed over the ground. The most powerful technique involves viewing the angular resolution of these Čerenkov photons. This can yield accurate information concerning the primary γ-ray energy and direction of origin. Such telescopes employ large segmented mirrors with focal plane arrays or cameras of fast (ns resolution) photomultiplier tubes. These cameras permit parameterization of Čerenkov images, usually as an elliptical profile such that the major axis aligns with the direction of origin of the primary γ-ray. Single views of each image provide an event-by-event angular resolution of $\geq 0^{\circ}\!.15$ for typical pixel granularities of order $0^{\circ}\!.15$ to $0^{\circ}\!.25$. Imaging cameras have also achieved quite large fields of view (FoV) of order 5°, permitting survey observations. The detection of TeV γ-rays must be made however, against the dominating background of CRs. CRs also produce EAS, and hence Čerenkov images that are recorded by telescopes. Due to intrinsic differences in the development of EAS for γ-rays and CRs (hadronic interactions are present in the latter), Čerenkov images for CRs tend be more irregular in shape. Furthermore CRs also arrive isotropically, reflecting their randomized trajectories through interstellar and intergalactic magnetic fields. The imaging technique thus provides a powerful means to preferentially select "γ-ray-like" events via the use of directional and shape cuts. Following the pioneering performance of the Whipple[1] telescope, other major systems such as CANGAROO[2], CAT[3] and HEGRA[4] attained similar, or slightly improved performance, albeit at differing energy thresholds, $E \sim 0.25$ to a few TeV, owing to various mirror areas and other factors.

A further significant improvement in performance is attained from multiple or stereo views of the same Čerenkov image. By taking advantage of the uncorrelated nature of EAS image fluctuations, systems of telescopes, separated by ~ 100 m can achieve an angular resolution proportional to $\sim 1/\sqrt{n}$ for n views of the same image (Hofmann et al. 1999). For the same reasons, CR background rejection based on Čerenkov image shape also improves significantly. Typical background rejection fractions can exceed 99.99% after all cuts applicable to a pointlike source. The recently decommissioned HEGRA IACT-System (Pühlhofer et al. 2003), consisting of five four-meter diameter telescopes, demonstrated clearly the power of stereoscopy coupled with the use of large FoV

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[1] See `http://veritas.sao.arizona.edu/VERITAS_whipple.html` .

[2] See `http://icrhp9.icrr.u-tokyo.ac.jp/` .

[3] See `http://lpnp90.in2p3.fr/~cat/` .

[4] See `http://www-hegra.desy.de/hegra/` .

cameras. Other benefits of the stereoscopic technique include much improved energy resolution and also a reduction in systematics across the FoV, easing the task of performing surveys for new sources.

3. Galactic Sources: A Status Report

To date a total of eight Galactic candidates, listed in Table 1, are now observed as TeV γ-ray sources. Of those listed, only the Crab has been confirmed unambiguously by completely independent groups. I confine my list here to those sources appearing in the recent refereed literature (after 1995) and seen at a statistical significance $> 4.5\sigma$. For the most recent results the reader is directed to proceedings of the 28th International Cosmic Ray Conference in Japan[5], which suggest TeV emission from a few more candidates. Below I give a brief summary of each listed source, centering on our understanding of their TeV emission processes.

Crab: The Crab was the first source confirmed as a TeV emitter by the Whipple collaboration, and is now clearly detected by all groups active in the field. It is considered the "standard candle" in the field. The Crab flux has proved to be steady within instrument systematics, and exhibits an energy spectrum fitted by a pure power law over a remarkably large energy range 0.2 to 70 TeV (see e.g., Horns et al. 2004). The Crab is the most intensely studied pulsar/plerion and the unpulsed TeV flux is universally considered to arise from

Table 1. Summary of Galactic TeV sources. Confirmation is defined as positive detection by fully independent groups.

Name	Dist (kpc)	Flux[a]	Flux[b]	Signif.[c] (σ)	Confirmed?
		— Plerions —			
Crab	1.7	1.00	17.5	>50	Y
PSR B1706–44	1.8	1.14	20.0	12.0	Y
Vela	0.5	0.41	7.3	5.8	N
		— Shell-Type SNRs —			
SN 1006	1.8	0.49	8.5	7.7	N
RXJ 1713.7-3946	6.0	0.54	9.5	14.3	N
Cas A	3.4	0.03	0.55	4.9	N
		— XRB/Microquasars —			
Cen X-3	>5	0.64	11.2	4.5	N
		— Unidentified —			
TeV J2032+4130	?	0.03	0.59	7.1	N

[a] Flux in Crab units ($E > 1$ TeV)
[b] Flux ($E > 1$ TeV) $\times 10^{-12}$ ph cm^{-2} s^{-1}
[c] Statistical significance reported so far (refereed & unrefereed literature)

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[5] See `http://www.icrr.u-tokyo.ac.jp/icrc2003/` .

the inverse-Compton (IC) scattering of local (soft & synchrotron) photons by the shocked wind electrons filling the Crab plerion. These same electrons give rise to the very intense broad-band synchrotron spectrum extending from radio to X-ray energies. At the high energy end however the contribution of accelerated hadrons which lead to γ emission via π° decay could also become significant (Aharonian & Atoyan 1996a). This rather hard "hadronic component" may be required to explain the unbroken continuation of the Crab spectrum to $E > 50$ TeV. An IC cutoff would normally be expected due to electron cooling and the Klein-Nishina reduction in IC cross section.

PSR B1706–44: Steady TeV emission from this source was reported by CANGAROO and confirmed by the Durham group (Kifune 1995; Chadwick et al. 1998). As is the case for the Crab, the plerionic shocked pulsar wind could give rise to the unpulsed TeV emission, which is reportedly at similar levels to the Crab TeV flux. However, the very weak synchrotron X-ray flux, only recently seen by *Chandra* (Gotthelf et al. 2002) leads to a strong underprediction of the IC TeV for "reasonable" values of the magnetic field $B \sim 15\ \mu$G. One possible way out is for the high energy electrons to escape quickly to regions of lower B (Aharonian, Atoyan & Kifune 1997).

Vela: This is another plerion, whose unpulsed TeV emission has been interpreted in the electronic IC framework. Complicating matters somewhat, the CANGAROO discovery found the TeV emission $0\overset{\circ}{.}13$ offset from the pulsar position (Yoshikoshi et al. 1997), not far from its supposed birthplace. It is possible that a "relic" electron wind may be responsible for the plerionic synchrotron X-ray and IC TeV emission although this implies very low B fields (Harding, de Jager & Gotthelf 1997). An alternative hadronic picture is put forward by Aharonian (1999) as well as the unshocked electronic wind scenario of Aharonian & Bogovalov (2003).

SN 1006: This historical young shell-type SNR expanding into a relatively sparse environment exhibits a predominantly featureless X-ray spectrum, considered to be synchrotron emission. The bipolar morphology of SN 1006 in X-rays may trace out regions of more efficient electron injection. TeV emission has been seen from the slightly brighter (in X-rays) NE rim (Tanimori et al. 1998), and was initially attributed to the electronic IC process. However, as for PSR B1706–44 and Vela, very low $B < 10\ \mu$G fields are required to match the CANGAROO flux. It also appears that the hadronic component may play a significant role (Aharonian & Atoyan 1999; Berezkho et al. 2002), particularly given the recent high-resolution results of *Chandra* which favor higher $B > 10\ \mu$G fields in the post-shocked regions (Bamba et al. 2003).

RX J1713.7–3946: This older shell-type SNR appears to show TeV emission at its NW rim (Enomoto et al. 2002), not far from a neighboring molecular cloud with high ambient matter density. There is also strong non-thermal X-ray emission from this area. Interpretation was initially centered on the electronic IC component but more recently re-evaluation was made in strong favor of the hadronic origin for the accelerated particles. As is the case for SN 1006, the high resolution filamentary structure seen by *Chandra*, pointing to a high B field would certainly favor the hadronic component, as discussed by Uchiyama et al. (2003).

Cas A: The youngest shell-type SNR, Cas A, is one of the strongest radio sources. The HEGRA detection of TeV emission was made using a very deep exposure of >200 hours (Aharonian et al. 2001a). The TeV flux appears to favor a hadronic interpretation since the very high magnetic field in Cas A, a few mG, quenches strongly any electronic component (IC and bremsstrahlung) at $E > 1$ TeV (Atoyan et al. 2000; Berezhko et al. 2003). More detailed spectral information at $E > 5$ TeV should solve this issue.

Cen X-3: This high mass X-ray binary contains a 4.8-s pulsar in a 2.1-day orbit around an O-type supergiant and has also been seen by EGRET at low GeV energies. Neither the GeV or TeV fluxes appear modulated with the pulsar orbital period (Chadwick et al. 2000). The TeV production could come from a beam of relativistic hadrons interacting with ejected matter clumps from the companion star (Aharonian & Atoyan 1996b). Recent reanalysis of the TeV data does suggest some modulation of the TeV emission with the pulsar half-period from one night (Atoyan et al. 2002) for higher energy events. In general, the lack of modulation could point to a large scale source region, quite distant from the neutron star and Atoyan et al. (2002) also consider electronic IC components and possible ways to discriminate them from the hadronic scenario.

TeV J2032+4130: Discovered serendipitously in HEGRA IACT-System data (Aharonian et al. 2002; Rowell et al. 2004), TeV J2032+4130 is at present the only unidentified TeV source. Despite the fact that no multiwavelength counterpart is identified, its location within the extremely dense OB association Cygnus OB2 cluster could point to particle acceleration in such environments. Alternative explanations invoke a jet-powered microquasar scenario, for example a link to nearby Cygnus X-3, the EGRET source 3EG 2033+4118, or even an unseen plerion. The lack of an X-ray counterpart could suggest a hadronic source and deeper X-ray observations of the Cygnus OB2 region are in the pipeline (Butt et al. 2003). The discovery of TeV J2032+4130 is in fact a perfect example of the survey capabilities of present ground-based instruments, particularly those utilizing large fields of view and achieving arc-minute source location error boxes.

Overall, the interpretation of the Galactic TeV sources has invoked both the hadronic and electronic models. Except for the Crab, which is quite well understood in terms of the electronic synchrotron/IC framework, solid discrimination between the hadronic and electronic framework requires more accurate TeV spectral information covering a broader energy range, coupled with multiwavelength studies. In some cases the high resolution results from *Chandra* are certainly helping to constrain the electronic component. So far what is lacking is clear proof that the TeV Galactic objects are capable of accelerating hadrons to multi-TeV energies. Further improvements in sensitivity and energy coverage for ground-based instruments have therefore been sought after during the last five years or so. In particular, as well as aiming for a decrease in energy threshold to $E < 300$ GeV, it is now clear that sensitivity improvements at the high energy end, $E > 10$ TeV, are are also deemed vital to separating the hadronic from electronic emission processes.

4. New Ground-Based Instruments

The best ground-based systems operating up until 2002 achieved an angular resolution, energy resolution, energy threshold, and sensitivity of $\lesssim 0\overset{\circ}{.}1$, $\leq$15%, $\sim$250 GeV and $\sim 1\times10^{-12}$ ergs cm^{-2} s^{-1} ($E >$1 TeV, 50 hours, 5-σ) respectively. This flux sensitivity amounts to $\sim (5-10)\sigma$ / $\sqrt{hr}$ on the Crab. The so-called *next generation* instruments in ground-based γ-ray astronomy aim to realize roughly one order of magnitude improvement in sensitivity and reduction in energy threshold over present instruments. Four primary projects are now coming online. The HESS[6], VERITAS[7] and CANGAROO III[8] projects are employing the stereoscopic imaging technique. Data analysis techniques will be in general similar to that used by present instruments, in particular the stereoscopic aspects developed with the HEGRA IACT-System. These systems consist of arrays of $\geq$ 4 telescopes each with $\sim$ 100 m^2 segmented mirrors and imaging cameras of $\geq$500 pixels subtending $\geq 3°$ fields of view. All are expected to achieve energy thresholds in the range 50 to 200 GeV. The MAGIC[9] project comprises a single, very large telescope of mirror area ($>$200 m^2) in an effort to achieve an energy threshold $E <$ 50 GeV. Extra telescopes may be added to form a stereoscopic system. Figure 1 compares the sensitivities of present and next-generation (and beyond) ground-based instruments along with the next space-based detectors in the high energy regime, *GLAST*, *INTEGRAL* and *MEGA*.

As of 2003 Oct, HESS and CANGAROO-III have a number of telescopes running. They are expecting completion of their full 4-telescope arrays by 2004. VERITAS has just begun partial operation of their prototype telescope and MAGIC is also nearing completion, already taking engineering data. Both HESS and CANGAROO are situated in the southern hemisphere and as such are perfectly positioned to survey the Galactic plane for new sources. Searching for high energy counterparts to the numerous EGRET unidentified sources (Hartman et al. 1999) is a prime motivation. The angular resolution and FoV of HESS for example is expected to survey the inner plane ($|l| \leq 30°$, $|b| \leq 2.5°$) at the 0.1 Crab level in less than 200 hours observation time. HESS is also presently devoting large effort to confirmation of the all of the southern TeV sources listed above, all of which require confirmation at solid significance levels similar to early results on the Crab for full acceptance in the field.

Looking further into the future, already the expansion of HESS and the like is under full consideration. Several options ere now being considered as to how to improve the energy coverage and sensitivities even further. One such option given serious thought is the placement of a Čerenkov telescope at high mountain altitude, $>$ 4000 m, to approach the lowest possible threshold allowed by the technique $E \sim$ 5 GeV. The "5@5" proposal (Aharonian et al. 2001b) considers placing a HESS-like system (slightly bigger telescopes) at the ALMA

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[6] See `http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html` .

[7] See `http://veritas.sao.arizona.edu/veritas/` .

[8] See `http://icrhp9.icrr.u-tokyo.ac.jp/c-ii.html` .

[9] See `http://hegra1.mppmu.mpg.de/MAGICWeb/` .

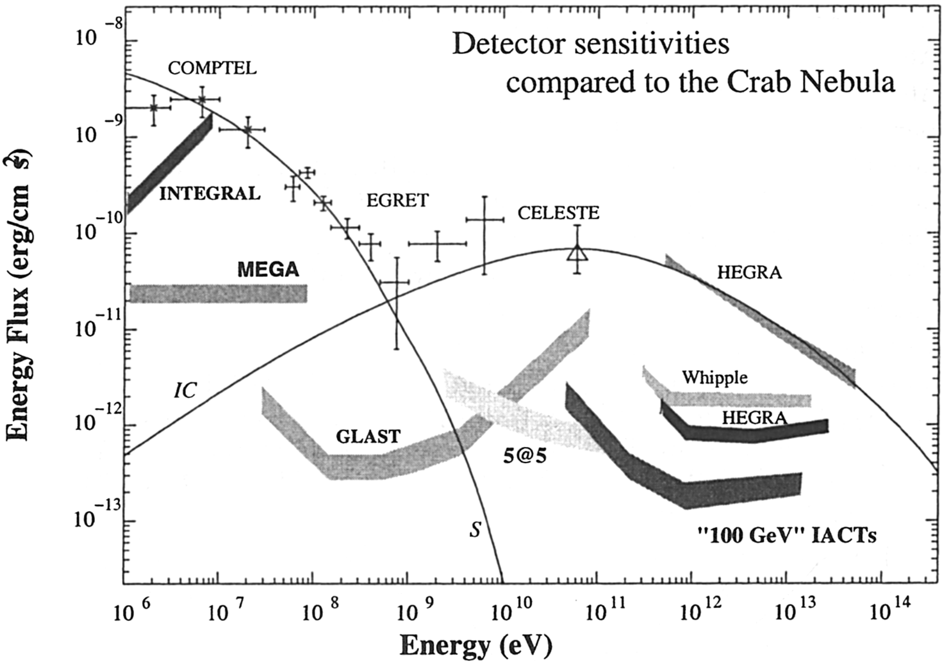

Figure 1. Comparison of detector sensitivies against the Crab broadband spectrum. “100 GeV IACTs” refer to “Next Generation” instruments described in the text (HESS, CANGAROO III, VERITAS and MAGIC). For the ground-based instruments, a 50-hour (5-σ) detection limit is required. For *GLAST*, *INTEGRAL* and *MEGA*, a 10^6-sec integration time is specified.

site in Chile (5000 m). Such a system could yield significant detections of Vela in just seconds, allowing for the first time γ-ray pulse timing activities. The follow-up of γ-ray bursts is also a major consideration.

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