Very high-energy gamma rays from gamma-ray bursts

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Very high-energy (VHE) gamma-ray astronomy has undergone a transformation in the last few years, with telescopes of unprecedented sensitivity having greatly expanded the source catalogue. Such progress makes the detection of a gamma-ray burst at the highest energies much more likely than previously. This paper describes the facilities currently operating and their chances for detecting gamma-ray bursts, and reviews predictions for VHE gamma-ray emission from gamma-ray bursts. Results to date are summarized.

Keywords: very high-energy gamma rays; gamma-ray bursts; atmospheric Cherenkov technique

1. Very high-energy gamma-ray astronomy

The gamma-ray region of the electromagnetic spectrum is generally regarded as starting at energies around 0.1 MeV, but it extends to around $10^{20}$ eV. This large energy range (15 decades) requires several different detection techniques, and it is these different techniques, rather than production mechanisms, that define the broad ranges of gamma-ray energy: low/medium, high, very high and ultra high. The definitions of these energy ranges are somewhat arbitrary as there is significant overlap between the energy ranges accessible to the different detection techniques; however, some basic definitions are provided in table 1.

In the very high-energy (VHE) regime, the dominant detection mechanism is the detection of the Cherenkov radiation produced in the atmosphere by the electromagnetic cascade produced by an incoming gamma ray. In the ultra high-energy (UHE) regime, the technique is to detect the electrons from the cascade as they penetrate to ground level. However, as we shall see, many particle cascade detectors are sufficiently sensitive to detect the particles from progenitor gamma rays at threshold energies of a TeV or even lower, well within the traditional VHE regime.

(a) Imaging atmospheric Cherenkov telescopes

The most successful technique of recent years has undoubtedly been the imaging atmospheric Cherenkov technique. A gamma-ray incident on the Earth’s atmosphere will produce an electromagnetic cascade, i.e. one consisting of

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electrons, positrons and photons. Owing to the high energy of the progenitor gamma ray, the charged particles in the shower are travelling at velocities in excess of the phase velocity of light in air. The result is the production of Cherenkov radiation, which consists of a coherent flash of blue light emitted in a cone along the direction of travel of the incoming gamma ray. Although the Cherenkov light is faint (the total Cherenkov light generated in the atmosphere by incoming cosmic rays and gamma rays is only approx. 10\(^{-4}\) of the total starlight) and lasts for only a few nanoseconds, it is possible to detect it using large mirrors as light collectors and photomultiplier tubes (PMTs) as light detectors.

The major problem for VHE gamma-ray astronomy until relatively recently was the overwhelming background caused by charged cosmic rays, which are more numerous than the gamma rays by a factor of \(\sim 10^4\). Such cosmic rays, not only protons but also including helium and other heavier nuclei, produce particle cascades in the upper atmosphere in a similar way to the gamma rays. The breakthrough was to use the fundamental differences between the airshowers induced by gamma rays and those induced by cosmic rays to distinguish between them. The latter, because of the hadronic nature of the progenitor particle, consist not only of an electromagnetic component but also hadron and muon components. The result is a Cherenkov light flash that is both broader and more irregular than that produced by a gamma ray. Imaging atmospheric Cherenkov telescopes (IACTs), therefore, employ an array of photomultipliers at the focus of a large mirror to image the Cherenkov light flashes and use a combination of their shape and spatial anisotropy to distinguish the cosmic- and gamma rays-induced showers from one another. In short, Cherenkov images from a point source of VHE gamma rays will be elliptical in shape with long axes that point towards the source.

The first telescope to employ this technique successfully was the Whipple telescope in Arizona (Cawley et al. 1990) and, applying analysis techniques devised by Hillas (1985), this telescope was used to make the first clear detections of VHE gamma-ray sources (Weekes et al. 1989; Punch et al. 1992). This was followed by detections made with other telescopes around the world (e.g. Tanamori et al. 1998; Aharonian et al. 1999; Chadwick et al. 1999) which, together with the results from the Whipple telescope, showed that the IACT had real potential. In particular, the HEGRA collaboration showed that advantages in relation to energy determination, source location and background discrimination could be obtained using an array of telescopes. Thus, the ‘standard’ design for the current generation of detectors consists of two or more imaging telescopes.

<table>
<thead>
<tr>
<th>energy band</th>
<th>low/medium</th>
<th>high</th>
<th>very high</th>
<th>ultra high</th>
</tr>
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<tbody>
<tr>
<td>range</td>
<td>0.1–30 MeV</td>
<td>30 MeV–100 GeV</td>
<td>100 GeV–100 TeV</td>
<td>&gt; 100 TeV</td>
</tr>
<tr>
<td>detectors</td>
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<td>silicon</td>
<td>atmospheric</td>
<td>particle</td>
</tr>
<tr>
<td></td>
<td>state</td>
<td>strip</td>
<td>Cherenkov</td>
<td>arrays</td>
</tr>
<tr>
<td>environment</td>
<td>space</td>
<td>space</td>
<td>ground</td>
<td>ground</td>
</tr>
</tbody>
</table>

Table 1. Gamma-ray energy bands (after Weekes 2003).
While there are disadvantages to IACTs compared with satellite-based telescopes—for instance, they can be operated only on dark, moonless nights and have a small field of view of a few degrees—there are also certain advantages. First, the detection area of these telescopes is very large, since it is effectively the area of the pool of Cherenkov light on the ground, which is some $10^4 \text{ m}^2$. It is this large collection area that makes it possible for ground-based telescopes to detect the low gamma-ray fluxes at these energies and enables ground-based telescopes to have good sensitivity to short-lived phenomena, such as GRBs. Secondly, because the axis of the core of the particle cascade is very close to the original path of the gamma ray, it is possible to locate sources to a high level of accuracy. The arrival direction of a single shower can be measured to an accuracy of $0.1^\circ$, and, using an array of telescopes, point sources can be located to an accuracy of ca 30 arcsec.

A further feature of IACTs (and indeed of all ground-based gamma-ray telescopes) should also be borne in mind, which is that the closer to the horizon observations are made, the larger the energy threshold of those observations. Conversely, due to geometric effects, the effective collecting area of the telescopes becomes larger at low elevations. Large zenith angle observations can therefore be used to advantage to observe the highest energy ‘tail’ of emission at energies of a few 10 s of TeV. In addition, simultaneous observations of an object made by telescopes in different locations can provide excellent spectral coverage. All the energy thresholds quoted here are for telescopes pointed at the zenith, unless they are for specific observations.

There are four major VHE gamma-ray collaborations operating IACTs around the world: H.E.S.S. and CANGAROO III in the Southern Hemisphere and VERITAS and MAGIC in the north. The basic characteristics of the instruments are shown in Table 2 and in Figure 1.

The US/Irish/UK VERITAS collaboration grew out of the highly successful Whipple collaboration. The VERITAS-4 array is currently under construction in Arizona. The first two telescopes have already proven their sensitivity with measurements of active galactic nuclei (J. Holder 2006, private communication). The third telescope is being commissioned, and the whole array is expected to be finished in early 2007.

The European MAGIC collaboration has built the largest telescope currently in operation, with a diameter of 17 m. This telescope was designed with two factors in mind—a low-energy threshold, and a lightweight structure to enable the telescope to slew quickly in pursuit of gamma-ray bursts, resulting in a fast repositioning time of approximately 40 s. A second telescope is currently under construction and this is expected to lower the present energy threshold of 50 GeV at zenith and improve background rejection. The first MAGIC telescope has

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**Table 2. Currently operating imaging atmospheric Cherenkov telescopes.**

<table>
<thead>
<tr>
<th>experiment</th>
<th>location</th>
<th>no. of telescopes</th>
<th>energy threshold (GeV)</th>
<th>field of view (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANGAROO III</td>
<td>Australia</td>
<td>3/4</td>
<td>250</td>
<td>4</td>
</tr>
<tr>
<td>H.E.S.S.</td>
<td>Namibia</td>
<td>4</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>MAGIC</td>
<td>La Palma</td>
<td>1</td>
<td>50</td>
<td>3.5</td>
</tr>
<tr>
<td>VERITAS</td>
<td>USA</td>
<td>4</td>
<td>100</td>
<td>3.5</td>
</tr>
</tbody>
</table>

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recently been used to make the first detections of VHE gamma rays from Mkn 180 (Albert et al. 2006a) and the BL Lac 1ES 1218+304 (Albert et al. 2006b), and the collaboration has discovered VHE gamma-ray emission from a microquasar, LSI+61 303 (Albert et al. 2006c).

The H.E.S.S. telescopes have been in operation in Namibia since 2003 and were built by a European/African collaboration, including Durham University in the UK. The telescopes’ first survey of the inner galactic plane, the only one to have been made at these energies so far, provided a large expansion of the number of known gamma-ray sources in our galaxy (Aharonian et al. 2005a). The telescopes have also been used to detect emission from the galactic centre (Aharonian et al. 2004a), produce the first image of any astronomical object at these energies (Aharonian et al. 2004b), discover the first VHE gamma-ray microquasar (Aharonian et al. 2005b) and observe AGN at unprecedented distances (Aharonian et al. 2006). Intriguingly, observations reveal some sources in our galaxy that are apparently without counterparts at other wavelengths (Aharonian et al. 2005c). In all, the H.E.S.S. telescopes have been responsible for the discovery of over 30 new VHE gamma-ray sources in the last few years, a quadrupling of the VHE gamma-ray catalogue. Slewing at a rate of 100° per minute, the telescopes are capable of pointing to a burst position within a few minutes of a burst alert. The H.E.S.S. II telescope is currently under construction; this 28 m diameter telescope will lower the threshold of the array to \(\text{ca} \ 20\ \text{GeV}\) and will also increase the sensitivity of the array at the current operating threshold of \(\text{ca} \ 100\ \text{GeV}\).

Figure 1. The four major imaging atmospheric Cherenkov systems. (a) CANGAROO III; (b) H.E.S.S.; (c) MAGIC; (d) VERITAS. Images courtesy of the respective collaborations.
The four telescopes of the CANGAROO III array are situated near Woomera in Australia, and observations involving more than one telescope have been underway since March 2004 (Mori 2005). Since one of the telescopes has a poorer efficiency than the other three telescopes due to its greater age, it is not operating at present. The Japanese/Australian collaboration has used the telescopes to observe VHE gamma-ray emission from the galactic centre (Tsuchiya et al. 2004) and from the SNR RX J0852.0-4622 (Enomoto et al. 2006).

(b) Solar array telescopes

An alternative to IACTs is to employ arrays of solar power station heliostats to detect the Cherenkov light produced by incoming gamma rays. Although the optics is not ideal, the advantage is that large mirror areas are available, which means that the energy thresholds of such instruments are low—typically a few tens of GeV. The chief method of distinguishing between gamma-ray and hadron-induced emission is to measure the lateral distribution of the light; Cherenkov light from hadron-induced airshowers has a greater lateral distribution than that from gamma-ray showers. In such systems, each heliostat, or a group of heliostats, must be focused on an individual PMT, which requires the use of secondary optics and leads to rather complex focal plane instrumentation.

Pioneering work on this technique was made by the CELESTE collaboration, who operated an array in the Pyrenees that was capable of detecting gamma rays with energies as low as 30 GeV (Paré et al. 2002). CELESTE closed in June 2004, and since then there have been two solar arrays in operation: STACEE in New Mexico (Hanna et al. 2002) and CACTUS in California (Hanna et al. 2002; figure 2a). During the summer of 2004, the primary mirrors of the STACEE detector were fitted with new motors that allow the detector to re-target to most observable GRB positions within 1 min.

The PACT telescope array in India, although not based around a solar array, employs rather similar techniques, in that sampling of the wavefront of the Cherenkov light by a large array of small telescopes is used to distinguish between cosmic and gamma rays (Bhat 2002).

(c) Particle airshower arrays

If the energy of the incoming gamma ray is sufficiently high, or at high enough altitudes, enough particles from the shower survive to ground level to allow them to be detected directly. Early telescopes using this method had high-energy...
thresholds of around 100 TeV, but more recent instruments have thresholds of a few TeV, and overlap in energy range with the IACTs. These telescopes cannot use imaging techniques to distinguish between gamma rays and hadrons, which results in much poorer background rejection than IACTs and a lower instantaneous sensitivity. They also have poor angular resolution, approximately 1°. However, they have two advantages over IACTs: they can be used to monitor large areas of the sky at once and they can be used during the day.

The Milagro telescope near Los Alamos in New Mexico detects the Cherenkov light produced in water by extensive airshowers (Smith 2005; figure 2b). It consists of 723 PMTs in a 6 million gallon tank of water which is covered in a light-tight barrier (Smith 2005). The PMTs are arranged in two layers in the tank to allow discrimination between gamma-ray and hadron-induced showers, resulting in a 90% background rejection. The detector has been proven with observations of the Crab nebula (Atkins et al. 2003), and has recently been used to detect a diffuse TeV source in the Cygnus region (Smith et al. 2005).

The Tibet AS-gamma experiment consists of an array of over 700 scintillation counters at an altitude of 4.3 km, giving the array an energy threshold of approximately 3 TeV. The array has been used to detect successfully the Crab nebula (Amenomori et al. 1999) and the two most prominent VHE gamma-ray emitting AGN, Mkn 501 and Mkn 421 (Amenomori et al. 2000, 2003).

2. VHE gamma-ray production in gamma-ray bursts

The EGRET spark chamber on board the CGRO detected photons of energy 30 MeV or more from seven GRBs (Dingus 2001). These GRBs were all among the GRBs with the highest fluence detected with BATSE, suggesting that the detection of high-energy radiation was sensitivity-limited rather than a property of the bursts themselves. The most famous of these bursts was GRB 940217, which produced an 18 GeV photon 90 min after the prompt emission (Hurley et al. 1994). It is therefore clear that at least some GRBs are capable of producing emissions that could, in principle, be detected by ground-based telescopes. However, there is no agreed explanation for the production of such high-energy radiation. A simple extrapolation of BATSE-observed GRB spectra to very high energies in an unbroken power law, without reference to any particular model, suggests that a telescope such as MAGIC could detect approximately 1 GRB per year (Galante et al. 2003).

In most VHE gamma-ray sources, the dominant VHE emission process is thought to be inverse Compton radiation. This can be produced either by relativistic electrons upscattering the synchrotron photons that they themselves have produced (the synchrotron self-Compton process or SSC) or by the upscattering of photons external to the synchrotron emission region (the external Compton, or EC, process). Another possible mechanism is photopion production, whereby relativistic protons produce pions, including π⁰, which will decay to produce gamma rays. The expectation for any emission from GRBs is that similar processes will apply.

GRB models in general suggest that there will be high photon densities in the bursts, so absorption of the gamma rays must be taken into account. Conversely, the observation of photons of a given energy will place a lower limit on the
bulk Lorentz factor, $\Gamma$, of the outflow, as the photon density depends on $\Gamma$. Lithwick & Sari (2001) used this to estimate the lower limits on the bulk Lorentz factors for a number of bursts observed with EGRET. The escape of TeV photons from a source would imply that $\Gamma \geq 850$ (Razzaque et al. 2004).

(a) Prompt emission

Several models predict emission up to around 10 GeV but little emission above that energy (e.g. Mészáros & Rees 1994; Pe’er & Waxman 2004; Wang & Mészáros 2006); while in principle this could be detected with ground-based instruments, in practice the thresholds of the current generation of instruments are not sufficiently low for a reliable detection. However, there are several models that predict emission at TeV energies.

Dermer et al. (2000) made detailed calculations of the non-thermal synchrotron and SSC spectra expected from a blast wave interacting with a uniform surrounding medium. They suggested that TeV photons from the SSC process during the prompt phase of the GRB would be approximately coincident with the prompt MeV emission, and that such an emission would have a hard spectral index as it would be sampling the harder SSC component. They found that, provided the $\gamma-\gamma$ opacity in the source is small, TeV SSC emission at levels comparable to that of the prompt MeV synchrotron radiation would be emitted from GRBs. Another model, employing a monoenergetic beam of electrons, also suggests that the sub-MeV emission is dominated by synchrotron radiation, and that approximately 10% of the total GRB energy should be converted via the IC process into photons of energy 100 GeV and above (Derishev et al. 2001).

Fragile et al. (2004) studied the implied energy requirements for TeV gamma rays and their associated electrons and protons. They concluded that photopion production was unlikely to be an efficient mechanism for VHE gamma-ray production, and that either IC scattering or proton-synchrotron radiation were the most efficient.

The influence of neutrons on gamma-ray bursts has also been considered, since these would be expected from a burst with a supernova progenitor. Derishev et al. (1999) analysed the dynamics of a neutron–proton relativistic wind, paying particular attention to the fireball. They concluded that inelastic collisions between protons and neutrons would result in pion production. Although the bulk of the radiation emitted from the fireball would consist of relatively soft photons, they calculated that a small portion of the energy would be carried away by photons produced from pion decay, and that in the observer’s rest frame these would have an energy of around 100 GeV.

(b) Afterglow emission

Since the famous 18 GeV photon from GRB 940217 arrived 90 min after the initial burst, many models have focused on the production of VHE gamma rays during the afterglow phase of a burst. Zhang & Mészáros (2001) expect that, in circumstances where the electron IC emission dominates over the electron-synchrotron component, there will be significant high-energy emission up to approximately one month after the burst extending to energies of 100 s of GeV. They consider the dominance of electron IC emission the most likely explanation of the delayed GeV emission from GRB 940217.
Another burst, GRB 941017, showed an unusually hard spectral component extending to 200 MeV or more during the early afterglow phase. This is hard to explain as synchrotron emission from shock-accelerated electrons (González et al. 2003). Proton-induced emission has been invoked to explain this emission (Waxman & Bahcall 2000). An alternative explanation is that electrons in the forward shock IC scatter optical photons emitted by the reverse-shock electrons and create the observed spectrum (Pe’er & Waxman 2004). Different scenarios to account for the high-energy component result in different predictions, but in all cases the predicted fluxes at TeV energies would be well within the grasp of the present generation of ground-based instruments.

Wang et al. (2001) calculated the IC emission from GRB shocks produced when the ejecta encounters the external interstellar medium. They considered several different IC processes, and concluded that the SSC emission from reverse shocks dominates in the MeV–GeV band, but that SSC emission from the forward shock and from two IC processes—scattering of reverse-shock photons by the forward-shocked electrons and vice versa—will become increasingly dominant for a reasonably steep distribution of shocked electrons. This is found to be true for a wide range of shock parameters, and leads to the prediction that most GRBs should produce strong TeV emission during the early afterglow phase. The model of Razzaque et al. (2004) predicts photons with a typical cut-off energy between 10 and 100 GeV during the prompt phase, the cut-off being caused by photon–photon interactions within the shock region. However, they also expect delayed emission due to the IC scattering of infrared and microwave background photons. This emission would occur 10–100 s after the initial burst and would be mainly in the 1–100 GeV energy range.

It was proposed some time ago that GRBs are likely sites for the production of ultra high-energy cosmic rays (UHECRs; Waxman 1995) and that UHECRs, interacting with the microwave background, could produce GeV–TeV photons (Waxman & Coppi 1996). Indeed, Wick et al. (2004), echoing the ‘single source’ model of Erlykin & Wolfendale (1998), have suggested that the high-energy cosmic rays in the vicinity of the ‘knee’ in the CR spectrum ($E \approx 10^{14}$ eV) in our galaxy could be produced by a single GRB ≈ 1 kpc from the Earth. Dermer (2006), noting that the X-ray lightcurves of approximately 30% of the Swift GRBs show a rapid decline some hundreds of seconds after the burst trigger, has shown that this would be expected if cosmic rays are accelerated in GRBs, due to a rapid depletion of the hadronic component by means of photopion production approximately $10^2$–$10^4$ s after the GRB explosion. The result would be the production of strong TeV emission from proton-synchrotron radiation and photopion cascades, starting minutes to hours after the prompt phase of the GRB.

\( (c) \) Gamma-ray burst remnants

If, as expected, GRBs occur within our galaxy, then there should be GRB remnants left behind. Chandra X-ray observations of the morphology of SNR W49B led to the suggestion that this could be one such remnant (Ioka et al. 2004). Assuming that GRBs are sources of UHECRs, there should be significant GeV–TeV emission from the remnant produced by IC emission from beta-decay electrons. This emission would be extended, and GeV–TeV imaging of the remnant would help to constrain the structure of the assumed GRB jet.

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Recent observations of an unidentified VHE gamma-ray source in our galaxy by the H.E.S.S. collaboration (Aharonian et al. 2005c), H.E.S.S. J1303-631, have prompted suggestions that this may be a GRB remnant (Atoyan et al. 2006). Through detailed calculations of particle diffusion and radiation processes, they conclude that it is quite possible, even likely, for a GRB remnant to produce strong GeV–TeV emission without any appreciable synchrotron emission. Thus, H.E.S.S. J1303-631 could be explained by a 10–20 kyr old GRB remnant approximately 10–15 kpc from Earth. Their primary prediction for the TeV observations is that the spectrum for the remnant as a whole should be significantly harder than the energy spectrum measured for the central region of the source. They also predict an unusually hard spectrum between 10 and 100 GeV, which would be best determined with either GLAST or the next generation of ground-based gamma-ray telescopes.

Local GRBs may occur at a fairly high rate, approximately $10^{-4} \, \text{yr}^{-1}$, which would have had an impact on the evolution of life on Earth (Thomas & Melott 2006). The confirmation of extended unidentified TeV sources as GRB remnants would enable a refined estimate of the galactic GRB rate to be made.

### 3. Photon–photon absorption

Although it may well be likely that GRBs produce VHE gamma rays, their detection at Earth is constrained by their absorption by other photons. The interaction

$$\gamma + \gamma \rightarrow e^+ + e^-$$

will occur provided that there is sufficient energy for pair production in the rest frame of the interaction (Nikishov 1961; Stecker et al. 1992). In the case of TeV gamma rays, the pair-production process is maximized when the soft photon is in the infrared range; for example, for a 1 TeV photon this corresponds to 2.2 μm. Such extragalactic infrared background radiation comes directly from stars, and also from optical emission which is partly absorbed and re-emitted at longer wavelengths by dust. The optical depth of this process increases with redshift and has a strong energy dependence. In addition to the attenuation of the flux, from around 0.1 to 1–2 TeV a significant steepening of the spectrum will result. The exact form of the spectral steepening and attenuation is dependent on the spectral energy distribution of the infrared background radiation. Recent measurements by the H.E.S.S. collaboration from two blazars at redshifts of 0.186 and 0.165 suggest that the attenuation may not be as severe as first believed (Aharonian et al. 2006). However, since GRBs have a median redshift of approximately 1 (Friedman & Bloom 2005), this is still a strong constraint on VHE gamma-ray observations. Knowledge of the redshift of a GRB is therefore important for the accurate interpretation of VHE gamma-ray results. Conversely, the detection of VHE gamma rays from a GRB would provide an upper limit on its redshift.

### 4. VHE gamma-ray observations of GRBs

If one assumes that GRBs produce prompt VHE gamma rays, and that only those with redshift 0.25 or more could be detected with ground-based instruments, then taking into account the duty cycle of IACTs, one concludes
that one to two GRBs will occur at suitable times and zenith angles for ‘prompt’ emission to be observed by a given IACT each year. Rather more afterglow observations are possible, perhaps 4 or 5 per year, but this is highly dependent on the delay between the prompt emission and any afterglow emission. An array such as Milagro, because it observes a large area at any one time and can observe during the moonlit hours and during the day, will be ‘on target’ for a much larger number of close GRBs, but the higher energy threshold and lower sensitivity of such particle detector telescopes mitigate this advantage.

The Whipple Collaboration was one of the first to be involved in a serious search for VHE gamma-ray emission from GRBs, starting in 1978 using first-generation gamma-ray telescopes over long baselines (Porter & Weekes 1978). Two approaches were taken to the attempt to detect emission from GRBs using the later Whipple imaging telescope. The first was to search for counterparts to GRBs detected with the BATSE experiment (Connaughton et al. 1997) and the second was to search through a 4-year database from the telescope for bursts on a 1 s time-scale detected serendipitously (Connaughton et al. 1998). Both searches were unsuccessful, but it should be noted that the minimum detectable fluence above 400 GeV ($6 \times 10^{-9}$ erg cm$^{-2}$) was comparable to that of BATSE at much lower energies. An attempt to detect afterglow emission from GRB 010222 with the HEGRA telescopes also proved negative (Götting & Horns 2003).

The STACEE telescope was used to make afterglow observations of 14 bursts between 2002 and 2005. Of particular interest are the observations of GRB 050607, which started just 3 min 11 s after the initial emission was detected with Swift (Jarvis et al. 2005). The burst was tracked for 1150 s and an upper limit was placed on the time-averaged flux of approximately $4.4 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ above 100 GeV, assuming a source spectral index of $-2.8$. This is about six times the flux from the Crab nebula. The H.E.S.S. telescopes have also been used to make afterglow observations of 14 bursts over the last 18 months, one at a redshift of 0.089 and one within 16 min of the prompt trigger (Tam 2006).

The record for the most rapid slew to a GRB by an IACT is held by the MAGIC telescope, which was able to move to the position of GRB 050713a 40 s after the burst onset (Albert et al. 2006d); see figure 3. The burst was followed until twilight, a total of 37 min observation. No evidence for emission above 175 GeV was obtained, but as the redshift of the burst was unknown, interpretation of the flux limit obtained is necessarily curtailed. The flux upper limit is compatible to the assumption of an unbroken power law extending from a few hundred keV to a few hundred GeV.

The best evidence for VHE gamma-ray emission available so far comes from a water Cherenkov telescope. The Milagrito telescope, a forerunner of the larger Milagro telescope, showed an excess of 18 events coincident spatially and temporally with GRB 970417a, as shown in figure 4 (Atkins et al. 2000). The expected background was $3.46 \pm 0.11$ events, so the excess had a chance probability of $2.8 \times 10^{-5}$ of being a background fluctuation. However, the probability of observing an excess at least this large for any one of the 54 burst locations analysed was $1.5 \times 10^{-3}$, or slightly over 3σ. Upon identifying GRB 970417a as a candidate VHE-emitting burst, a search for emission over time-intervals of 1 h, 2 h and 1 day was conducted, but there was no evidence for afterglow emission. If photons with energies greater than a few hundred GeV were indeed detected from this relatively weak BATSE burst, this would imply
that the emission at very high energies was at least an order of magnitude greater than that at MeV energies. A later search for emission from 20 GRBs occurring between December 2004 and December 2005 with the more sensitive Milagro instrument proved negative (Saz Parkinson 2006).

The Tibet airshower array, an earlier version of the Tibet AS-γ array, was used to search for clusters of events above 10 TeV coincident with BATSE bursts from June 1990 to September 1992 (Amenomori et al. 1996). Several burst-like events coincident with BATSE events were observed, but uncertainties in the

![Figure 3. MAGIC excess event rate compared with Swift BAT observations of GRB 050713a. The dashed vertical line shows the start of the MAGIC observations (Albert et al. 2006d; reproduced by permission of the AAS).](image)

![Figure 4. Number of events recorded by Milagrito during the BATSE T90 interval in overlapping bins of 1°.6 in the vicinity of GRB 970417a (Atkins et al. 2000; reproduced by permission of the AAS).](image)
locations of the bursts were too great to associate the events unambiguously with GRBs. However, there may have been evidence for a significant deviation of the probability distribution from the background when all the burst data were superposed on one another. A search for transient events in a later, larger version of the array, Tibet-III, showed no evidence for the existence of any bursts (Amenomori et al. 2005).

5. Conclusions

In recent years, ground-based gamma-ray telescopes have improved in sensitivity by an order of magnitude or more, and energy thresholds have lowered. This makes the likelihood of the detection of VHE gamma rays from a GRB much higher than previously, and it can only be a matter of time before such a detection is made, despite the observational challenges. The combination of a VHE gamma-ray detection (or even upper limit) of a GRB with knowledge of the burst’s redshift will place important constraints on emission models.

The next generation of VHE gamma-ray telescopes, such as H.E.S.S. phase II, consisting of a single 28 m diameter telescope that will lower the H.E.S.S. energy threshold to approximately 20 GeV and MAGIC II, which will have a similar effect for the MAGIC telescopes, are currently under construction. These low-energy threshold instruments increase the prospects for the detection of VHE gamma rays from GRBs even further, and together with GLAST will provide unprecedented spectral coverage.

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