Gamma-Ray Bursts Above 1 GeV

Matthew G. Baring\textsuperscript{1,2}

\textsuperscript{1}LHEA, NASA/Goddard Space Flight Center, Greenbelt, MD 20770, USA
\textsuperscript{2}Compton Fellow, Universities Space Research Association

Abstract

One of the principal results obtained by the Compton Gamma Ray Observatory relating to the study of gamma-ray bursts was the detection by the EGRET instrument of energetic (>100 MeV) photons from a handful of bright bursts. The most extreme of these was the single 18 GeV photon from the GRB940217 source. Given EGRET’s sensitivity and limited field of view, the detection rate implies that such high energy emission may be ubiquitous in bursts. Hence expectations that bursts emit out to at least TeV energies are quite realistic, and the associated target-of-opportunity activity of the TeV gamma-ray community is well-founded. This review summarizes the observations and a handful of theoretical models for generating GeV–TeV emission in bursts sources, outlining possible ways that future positive detections could discriminate between different scenarios. The power of observations in the GeV–TeV range to distinguish between spectral structure intrinsic to bursts and that due to the intervening medium between source and observer is also discussed.

1. Introduction

Gamma-ray bursts (GRBs) have intrigued observers and confounded theorists ever since their discovery over twenty years ago (Klebesadel, Strong and Olsen 1973). Despite a plethora of source observations by over a dozen different experiments, these fascinating transients remain enigmatic phenomena. While the results obtained by the Compton Gamma Ray Observatory (CGRO) dramatically improved our observational database, they perpetuated the confused picture we have of GRBs, and ushered in a new age of controversy. Bursts emit predominantly in the 10 keV–10 MeV band (for spectra, see Band et al. 1993, or the BATSE 1B spectroscopy catalogue of Schaefer et al. 1994), with durations normally between milliseconds and several minutes and sometimes millisecond variability: see the BATSE 1B catalogue of Fishman et al. (1994) for an illustration of the complexity and diversity of their time histories.

The contribution of CGRO to the GRB paradigm has been threefold. First, the accumulation of a more substantial burst population by one experiment (BATSE) has permitted a more precise determination of their celestial angular and \( \log N \cdot \log S \) distributions, leading to the confirmation that bursts are indeed isotropic, but that they are relatively scarce (Meegan et al. 1992) at low fluxes (i.e. presumably large distances). The simplest explanation for this fact is via the hypothesis that bursts are cosmological in origin: this spawned the subsequent tergiversation of the GRB community’s perspective from the pre-CGRO view that bursts arose near neutron stars in the disk of our galaxy. The second definitive advance to our knowledge of bursts by CGRO was the detection by EGRET of hard gamma-rays well above 10 MeV (discussed at more length in the next section) from a high percentage of bright BATSE sources,
suggesting that the GRB phenomenon is not exclusively the domain of low energy gamma-ray astronomy. Third, the evidence for hard X-ray absorption features in the early KONUS observations (see Mazets et al. 1981, and Fenimore et al. 1988 for higher spectral resolution GINGA detections of such features) was not reproduced in the BATSE data, substantially diminishing the strongest evidence in the pre-CGRO era for the galactic neutron star scenario.

Despite these advances, the distance scale for bursts was still not unequivocally determined, and GRBs remained the only class of transient astronomical sources that were believed to emit purely in gamma-rays. Searches in the radio, optical and X-ray bands for convincing transient or quiescent steady-state counterparts to bursts (e.g. see papers in Paciesas and Fishman 1991) had proved negative, and the Holy Grail of GRB astronomy remained elusive. This year the situation changed with the improvement of burst localizations by BeppoSAX to a few arcminutes. This led to the sensational discovery of X-ray (Costa et al. 1997) and optical (Groot et al. 1997; van Paradijs et al. 1997; Guarnieri et al. 1997; Djorgovski et al. 1997) counterparts to the GRB 970228 event (the yymmdd notation denotes burst dates). These sources were ascertained to be persistent but variable, exhibiting decays on timescales of the order of a month or so. Since then, another burst provided counterpart detections, GRB 970228, which revealed Mg and Fe absorption lines in optical observations by the Keck telescope. The $z=0.77$ and $0.83$ redshifts of these lines (Metzger et al. 1997) are attributed to interstellar media associated with galaxies intervening between the burst and the observer, or perhaps also the host galaxy for GRB970228. If these associated sources are indeed true counterparts, this result provides compelling evidence for the cosmological origin of bursts.

Given these developments, it is natural to ask what role can TeV gamma-ray astronomy play in resolving outstanding issues and refining our understanding of burst sources? This paper outlines the expected impact that positive detections of bursts by ground-based Atmospheric Čerenkov Telescopes (ACTs) can make on the gamma-ray burst field in the foreseeable future, in particular how they can constrain model parameters and source distances. The EGRET observations that have already motivated GRB searches by extant experiments are reviewed, and the handful of models that address super-GeV emission in limited fashions are discussed. Spectral signatures expected from pair production attenuation internal to sources will be summarized, and compared with the spectral absorption anticipated from interactions with cosmological background radiation fields. While the recent observations of optical counterparts to BeppoSAX bursts with inferred significant redshifts favours an emphasis on cosmological scenarios, bursts of galactic halo origin will also be discussed for completeness.

2. EGRET Observations and TeV Upper Limits

Prior to the launch of the Compton Gamma-Ray Observatory in 1991, there were no detections of super-GeV photons coming from gamma-ray bursts, with the highest energy photon recorded by the GRS spectrometer on the Solar Maximum Mission (SMM) being at around 80 MeV (Share et al. 1986); there were numerous detections at lower energies (e.g. Nolan et al. 1983). This prompted the popular perception that bursts were short-lived hard X-ray/soft gamma-ray phenomena, with little relevance to ground-based experiments. This misconception could, in principal, be supported by results from the BATSE instrument on CGRO, which, while it routinely observes GRB spectra extending up to and above 1 MeV, demonstrated that most bursts exhibit spectral steepening at a variety of energies between 50 keV and few hundred keV (Band et al. 1993; see also Mallozzi et al. 1995 for the “$\nu F_{\nu}$-peak” distribution and Schaefer et al. 1994 for the BATSE 1B spectroscopy catalogue).
The observations by the EGRET and COMPTEL experiments on board CGRO changed this picture dramatically. Detections of 11 bursts (e.g. see Schneid et al. 1996 for a recent listing) by the EGRET spark chamber and/or TASC extended the spectral range of interest to the hard gamma-ray domain. In addition, COMPTEL has seen (e.g. Hanlon et al. 1994) over 20 bursts in the 300 keV–15 MeV range. EGRET has detected emission above 50 MeV from four of the brighter GRBs triggered by BATSE; all are consistent with power-law spectra extending to as high as 1.2 GeV, in the case of GRB 930131 (Sommer et al. 1994), and 3.4 GeV for GRB 940217 (Hurley et al. 1994). The GRB 940217 source is best known for exhibiting delayed or prolonged high energy emission, detected 80–100 minutes (i.e. more than one full earth orbit of CGRO) after the initial trigger, including a photon of energy 18 GeV (Hurley et al. 1994) that is not markedly inconsistent with the extrapolation of the power-law continuum. Not only did this observation further expand the spectral range of bursts, it opened up the possibility of extended emission in the time domain. This property has motivated recent searches for high energy gamma-ray emission by ground-based ACTs following notification via the BACODINE alert network (discussed by Cline et al. in these proceedings) of BATSE burst triggers. Some evidence for delayed high energy emission pre-dated GRB 940217, with the observation (Dingus et al. 1994) of a single 10 GeV photon that could have been associated with GRB 910503.

Fig. 1: The integral fluxes for six of the eleven EGRET burst detections (a depiction after Hurley 1996). The solid lines are the confirmed power-laws, as taken from the data compilation in Baring and Harding (1997b), while the dashed extrapolations are provided to indicate fluxes in the TeV range. The filled circles denote the single “delayed” photons observed to be consistent with the positions of two bursts, GRB910503 (Dingus et al. 1994) and GRB940217 (Hurley et al. 1994). The current threshold and sensitivity for ACT observations of bursts is indicated by the “ACT” box, and is taken from the Whipple rapid searches (Connaughton et al. 1997).
The general relationship of EGRET source spectra to searches by ground-based ACTs can be illustrated via the collections of hard gamma-ray portions of GRB spectra in Figure 1. These EGRET sources are the ones with better detection statistics, and their source parameters (differential fluxes at 1 MeV, spectral indices and maximum energies, tabulated in Baring and Harding 1997b) are obtained from the source papers of Schneid et al. (1992: GRB 910503), Kwok et al. (1993: GRBs 910601 and 910814), Sommer et al. (1994: GRB 930131, the “Superbowl burst”), Hurley et al. (1994: GRB 940217) and Catelli et al. (1996: GRB 950425). Note that a conservative approach is adopted here, with the delayed high-energy emission being distinguished from the power-law emission; such a choice is motivated by the possibility that the “delayed” photons may actually be from prolonged components that are distinct from the lower energy power-laws. Other EGRET sources have statistics that are too poor to effect reliable extensions of their spectra to the TeV range; extrapolations of the upper end of BATSE spectra suffer from the same problem. It is clear from the EGRET (and also BATSE and COMPTEL) data that there have been no attenuation-type turnovers or cutoffs observed in a GRB spectrum. High energy gamma-ray emission may therefore be common in bursts, if not universal: the EGRET detection rate is consistent (Dingus 1995, though this inference is subject to poor statistics) with all bursts emitting above about 30 MeV.

The extrapolations to TeV energies indicate that half of these bursts would have been visible to Čerenkov telescopes, assuming that these sources intrinsically emit at such energies and that there is no internal or external absorption of their radiation. The fact that these were several orders of magnitude above current ACT sensitivities is strong motivation for a TeV search program. Such a quest began in earnest in early to mid 1995 by the Whipple team, made possible by the establishment of the BACODINE notification network. Unfortunately, this post-dated all but one of the bursts depicted in Figure 1, so that target-of-opportunity exposures for these sources were not possible. Since the beginning of this program, the Whipple team has reported (Connaughton et al. 1995, 1997; Boyle et al. 1997) only negative results from their searches following fast telescope slewing prompted by BATSE triggers. The upper bounds to integral fluxes so obtained for several bursts are approximately represented by the “ACT” box in Figure 1, and pertain to observations made, at earliest, starting two minutes after the BATSE events. HEGRA has a similar program, also with negative results (Padilla et al. 1997) in both tracking and archival searches, and the status of the BIGRAT/CANGAROO initiative in this direction is reported in Dazeley et al. (1997). While the ACT sensitivity box is tailored to Whipple’s conditions, it provides a rough guide to other experiments such as HEGRA and CANGAROO, which have higher thresholds and consequently better flux sensitivity (denoted by the two arrows attached to the box). MILAGRO will have a slightly worse sensitivity, but this will be compensated for by its greater potential detection rate due to its large field of view.

3. A Pocketful of Models

Theoretical predictions of gamma-ray emission above 1 GeV are extremely sparse, largely due to the paucity of data in this range. Since the relevant observations postdate the launch of CGRO, only models of the cosmological fireball genre address super-GeV emission, albeit cursorily, with limited spectral development in most cases. Such models, first proposed by Cavallo and Rees (1978) and considered by numerous researchers since, usually involve a central catastrophic event such as the gravitational coalescence of neutron star or neutron star/black hole binaries (e.g. Paczyński, 1986; Eichler et al. 1989), or perhaps partial failure and collapse of a supernova
onto its compact core (Woosley, 1993). In either case, roughly a solar mass of energy is released in a very small, optically thick volume, thereby rapidly thermalizing to relativistic temperatures (10 MeV or so, Paczyński, 1986). This energy naturally must disperse adiabatically, and the resulting expansion of baryons and pairs generates relativistic bulk motions, i.e. a fireball. Temperatures around $\sim 20$ keV are usually achieved (e.g. Paczyński, 1986; Goodman, 1986) in the adiabatic cooling of fireballs, blue-shifted to MeV energies by the bulk motion of the plasma outflow. This is unlike the observed non-thermal spectra of bursts, leading immediately to a problem with pure fireball models, though radiative transfer effects (Carrigan and Katz, 1992) may produce steep high energy tails.

In subsequent refinements to fireball models it was observed that those with significant baryonic content are relatively inefficient at $\gamma$-ray production (Shemi and Piran, 1990). This property motivated the formulation of “blast-wave” impact models (e.g. Mészáros and Rees, 1993a,b), where the fireball sweeps up material from the surrounding interstellar medium, creating one or several shocks, much like the propagation of supernova ejecta. The kinetic energy of the fireball is then extracted in non-thermal form via dissipative action of such shocks in the formation of quasi-isotropic populations of particles through Fermi acceleration. These particles efficiently create non-thermal radiation with multiple-component broken power-law spectra. Mészáros and Rees (1993b, see also Mészáros, Rees and Papathanassiou 1994) envisaged synchrotron radiation generally in the optical to X-ray range, and an inverse Compton “image” of the synchrotron continuum in the $\gamma$-ray range. This scenario yields spectral indices as low as 3/2, which are quite representative of the EGRET data. A significant deficiency of this model is that it does not define a characteristic energy for the peak of the $\nu$-$F_\nu$ spectrum that is restricted to the BATSE energy range. TeV band observations have the potential to restrict source parameters such as density $n$, field strength $B$ and bulk Lorentz factor $\Gamma$.

None of the remaining handful of models for super-GeV emission make detailed spectral predictions nor provide well-constrained flux estimates. Katz (1994) suggested that the impact of fireballs with dense clouds (with $n \gtrsim 10^9$ cm$^{-3}$) spawned by their progenitors, perhaps as a wind, could yield gamma-ray emission via $\pi^0$ decay. Such densities are possible on subparsec scales if the clouds are sufficiently massive ($\sim M_\odot$), and the result would be a delayed hard gamma-ray signal. Mészáros and Rees (1994) conjecture that the super-GeV emission is a delayed signal from the impact of the fireball with the ISM while the MeV radiation is generated by shocks internal to the fireball. Waxman and Coppi (1996) proposed that cascading of ultra high energy ($\gtrsim 10^{19}$ eV) cosmic rays off infra-red and cosmic microwave background fields can generate delayed GeV–TeV emission from cosmological bursts. This becomes possible only if the bursts have fields in excess of $10^5$ Gauss, below which Fermi acceleration of cosmic rays to such high energies is not possible. While they make no spectral predictions, the expectations of this model can be assessed from the calculations that Protheroe and Stanev (1993) performed for such cascading in the context of active galactic nuclei. They determined that flat emission spectra were possible, with cutoffs that were quite dependent on the source distance. For this situation, observations by ACTs may be able to provide distance determinations for bursts.

4. Spectral Characteristics in the GeV–TeV Band

While these more-focussed gamma-ray burst models have provided few spectral predictions, there exist more global calculations that provide general guides for TeV gamma-ray astronomers of the expectations for GRB fluxes and spectra. These results hinge on the transparency or the
opacity of high energy source photons to two-photon pair production $\gamma\gamma \rightarrow e^-e^+$, and have been studied rather extensively because of their informative, more-or-less model-independent nature. In the subsequent presentations of this section, bursts will be assumed to intrinsically emit out to energies of 1 TeV–10 TeV or higher; if reality should prove otherwise, the relevance of ACT observations to GRB studies will be very limited.

4.1. Opacity to internal pair production

Attenuation by pair creation in the context of GRBs was first explored by Schmidt (1978). He assumed that a typical burst produced quasi-isotropic radiation, and concluded at the time that the detection of photons around 1 MeV limited bursts to distances less than a few kpc, since the optical depth scales as the square of the distance to the burst. The EGRET observations of emission above 100 MeV indicated that Schmidt’s analysis needed serious revision, particularly since BATSE’s determination of the spatial isotropy and inhomogeneity of bursts (e.g. Meegan et al. 1992) implied that they are either in an extended halo or at cosmological distances. Consequently their intrinsic luminosities, and therefore their optical depths to pair production for isotropic radiation fields, are much higher than was previously believed.

In the wake of this apparent conflict, the suggestion (e.g. Fenimore et al. 1992) that GRB photon angular distributions were highly beamed and produced by a relativistically moving or expanding plasma emerged. This hypothesis builds on the property that $\gamma\gamma \rightarrow e^-e^+$ has a threshold energy $E_1$ that is strongly dependent on the angle $\Theta$ between the photon directions: $E_1 > 2m_e^2c^2/[1 - \cos \Theta]E_2$ for target photons of energy $E_2$. Hence radiation beaming associated with relativistic bulk motion of the underlying medium can dramatically reduce the optical depth, $\tau_{\gamma\gamma}$, internal to sources at enormous distances from earth, suppressing $\gamma$-ray spectral attenuation turnovers, and blue-shifting them to energies above those detected. Various determinations of the bulk Lorentz factor $\Gamma$ of the medium supporting the GRB radiation field have been made in recent years, mostly concentrating (e.g. Krolik and Pier 1991, Baring 1993, Baring and Harding 1993) on the simplest case where the angular extent of the source was of the order of $1/\Gamma$, with an infinite power-law burst spectrum $n(\varepsilon) = n_\gamma \varepsilon^{-\alpha}$, where $\varepsilon$ is the photon energy in units of $m_e c^2$. Under such assumptions, the pair creation optical depth takes the well-known form $\tau_{\gamma\gamma}(\varepsilon) \propto \varepsilon^{\alpha-1}\Gamma^{-(1+2\alpha)}$ for $\Gamma \gg 1$, so that large Lorentz factors suppress pair creation very effectively. Setting the optical depth to unity at the maximum energy observed by EGRET leads (e.g. Baring 1993; Harding 1994; Baring and Harding 1997b) to estimates of $\Gamma \sim 10 - 30$ for galactic halo sources and $\Gamma \sim 100 - 1000$ for cosmological bursts. The detailed analysis of pair production transparency for a broad range of source geometries by Baring and Harding (1997b) revealed that the optical depth $\tau_{\gamma\gamma}(\varepsilon)$ was only weakly-dependent on the opening angle $\Theta$ of relativistic expansions when $\Theta \gtrsim 1/\Gamma$, an effect that is due to restrictions on the $\gamma\gamma \rightarrow e^+e^-$ phase space imposed by causality.

4.1.1. The effects of sub-MeV spectral curvature on GeV–TeV spectra

Despite the expedient approximation of using infinite power-law spectra for most pair production analyses, most bursts detected by BATSE show significant spectral curvature in the 30 keV–500 keV range (e.g. Band et al. 1993). Furthermore, BATSE sees MeV-type (i.e. 500 keV–2 MeV) spectral curvature with significant frequency in bright bursts, including EGRET sources (e.g. see Schaefer et al. 1992). Such curvature could, in principle, reduce the opacity of potential TeV emission from these sources, via a depletion of target photons for the hard gamma-rays. This important consideration was discussed by Baring and Harding (1997a), who modelled GRB spectral curvature using broken power-laws as a first approximation. They
found that the presence of such curvature generally has minimal influence on the spectra (below 1 TeV) and inferred bulk motions for bursts of cosmological origin. This result followed as a consequence of there being a plentiful supply of target photons (at $E_1 \sim \frac{m_e^2 c^4 \Gamma^2}{E_2}$) above the BATSE range in sources at extragalactic distances. In contrast, for galactic halo sources, Baring and Harding (1997a) observed that source opacity may arise only in a portion of the 1 GeV – 1 TeV range, with transparency returning in the super-TeV range, resulting in the appearance of distinctive, broad absorption troughs. Such features would provide a unique identifier for bursts in halo locales.

Fig. 2: The attenuation, internal to the source, of a broken power-law spectrum for GRB 930131 at source distances typical of galactic halo (solid curves, $\Gamma = 15, 25, 25$) and cosmological (short dashed curves, $\Gamma = 800, 1200, 1600$) origin, and different bulk Lorentz factors $\Gamma$ for the emitting region. The spectra, plotted in the $E^2 f(E)$ (i.e. $\nu F_\nu$) format, are attenuated by the factor $1/(1 + \tau_{\gamma\gamma})$ (except for the $\Gamma = 1600$, long dashed line case) for optical depths whose form is in Baring and Harding (1997a). The source spectrum was modelled with a power-law broken at $E_B = 0.7$ MeV, with spectral indices $\alpha_l = 1.2$ and $\alpha_h = 2.0$. A low energy cutoff at 2 keV was used to mimic X-ray paucity. The filled circle denotes the highest energy EGRET photon at 1000 MeV (see Sommer et al. 1994). The current threshold and sensitivity for ACT observations of bursts is again indicated by the “ACT” box.

Attenuation of spectra appropriate to the “Superbowl” burst GRB 930131 are depicted in Fig. 2 for different $\Gamma$. Most of the curves depicted are for attenuation by a factor of $1/(1 + \tau_{\gamma\gamma})$, as is appropriate for source photons being distributed in a roughly spatially-uniform manner (i.e. including “skin effects”). The contrast between spectral shapes for cosmological and galactic halo bursts is striking. Absorption troughs appear in the 100 kpc cases and are quite distinct from the broken power-law structure in cosmological scenarios. The spectral indices above 1 GeV in the 1 Gpc examples are defined uniquely in terms of those at lower energies,
a property that can distinguish this internal absorption from the external photon absorption described just below. For both situations, GRB 930131 would have been easily detectable by ACTs if it had been observed in a slew search. An exponential attenuation case (for source distance $d = 1 \text{ Gpc}$) is also illustrated in the figure: similar examples are given in Baring and Harding (1997a). This corresponds to substantial spatial confinement of the target photons, and produces sharp cutoffs in cosmological scenarios that would render bursts undetectable by ACTs; halo bursts would still be detectable, however their absorption troughs would be much more pronounced. A diversity of such spectral shapes (e.g. troughs, shelves and turnovers) might be anticipated for GRBs. Clearly future observations and/or upper limits by ACTs will play a prominent role in constraining burst scenarios and model parameters such as $\Gamma$.

### 4.2. Absorption due to background fields

If $\Gamma$ happens to be large enough to permit emission out to TeV energies (it must be $\gtrsim 10^3$ for the $d = 1 \text{ Gpc}$ example of Figure 2), then spectra from cosmological bursts would suffer attenuation due to the external supply of infra-red (IR) background (and the cosmic microwave background, CMB) photons (Stecker and De Jager 1996, Mannheim, Hartmann and Funk 1996). This issue has been studied extensively for Mrk 421 and other blazars (e.g. see Stecker et al., in these proceedings), and the results can be directly mapped over to gamma-ray bursts. The absence of attenuation in extant data can provide upper bounds to the source redshift. For example, Stecker and De Jager (1996) concluded that the detection of an 18 GeV photon from GRB 940217 placed it at a redshift of $z \lesssim 2$, which is not very constraining for cosmological burst populations; such photons use the CMB as targets. Clearly, positive detections (or upper limits) in the TeV band would provide more powerful source distance diagnostics.

In anticipation of this, Mannheim, Hartmann and Funk (1996) computed the expected attenuation in GRB spectra for sources at significant cosmological redshifts $z$, and estimated detection rates for various TeV and super-TeV gamma-ray experiments. They contended that Whipple might expect to see one burst per year, but with its larger field of view, MILAGRO might detect around ten sources per year. The attenuation “templates” they produced are exhibited in Figure 3, and strongly resemble the exponential turnover case in Figure 2: exponential attenuation is the product of a unique burst distance in the bath of IR photons. These templates patently confirm that telescopes observing only above a few hundred GeV would be unable to detect bursts with redshifts greater than $\sim 0.5$. Experiments such as STACEE and CELESTE may therefore play a crucial part in studies of bursts if they are at high redshifts, as would be indicated by the Keck line observations discussed above, and also the time dilation analysis of Norris et al. (1994) for the BATSE event population. Note that the model-dependent details of photon/pair cascading (e.g. see Protheroe and Stanev 1993, for applications to active galactic nuclei) would probably make no significant qualitative changes to the shapes of these attenuation templates. One salient feature of the sharp spectral turnovers computed by Mannheim, Hartmann and Funk (1996) is that they depend on $z$, the (at present uncertain) details of the IR background, and the Hubble constant $H_0$. The connection of these quantities may prove valuable in the future. As absorption studies coupled with TeV observations of the blazars Mrk 421 and Mrk 501 (see several papers in these proceedings) have made great strides in constraining the IR background, when our knowledge of this is sufficiently improved, if optical telescopes like Keck can measure redshifts $z$ to burst counterparts, then constraints on the Hubble constant can be obtained. Realistically, it will be some time before this approach can yield results comparable to other methods for bounding $H_0$. 

Fig. 3: The attenuation factor template, as computed by Mannheim, Hartmann and Funk (1996, this Figure is an adaptation of their Figure 3), for absorption of GRB emission by pair production off external infra-red background photons (they use the IR model of MacMinn and Primack 1996). The factors, which are independent of the source spectral index, are presented for bursts at various redshifts at which blazars (as labelled) have been detected by EGRET. The Hubble constant for these templates was assumed to be $H_0 = 50$ km sec$^{-1}$ Mpc$^{-1}$.

5. Conclusion

The investigation of gamma-ray bursts with the atmospheric Čerenkov technique is clearly a fledgling field, awaiting the first confirmed detection. Yet it is anticipated that, as with their role in studying other cosmic objects, namely plerions associated with pulsars (discussed by Harding and De Jager in these proceedings), blazars, and now shell-type supernova remnants (SN1006: see Tanimori et al., these proceedings), Čerenkov telescopes will provide ground-breaking discoveries relating to gamma-ray bursts in due course: the future for the TeV gamma-ray astronomy of bursts is bright. Given the recent Keck line redshifts from a burst counterpart, it now appears unlikely that ACTs will play a key role in determining the global distance scale for gamma-ray bursts. However, current and future ground-based initiatives such as Whipple, HEGRA, CANGAROO, CAT, MILAGRO, STACEE and CELESTE, to name a few, and space missions such as GLAST, will provide key pieces of information constraining both distances to individual sources, and burst parameters such as the bulk Lorentz factor $\Gamma$, the underlying plasma density and magnetic field strength.

Detailed theoretical predictions of the dependence of TeV spectra on such parameters are currently sparse. Yet the generic absorption properties discussed in Section 4 provide strong guidelines for experimentalists. It is clear that observations in the $30$ GeV–$3$ TeV band can discriminate between pair production absorption that is internal to sources, for which there are strong correlations between the spectral shapes in different X-ray/gamma-ray bands, and opac-
ity due to external background fields of radiation. It is unlikely that multi-component models of hard gamma-ray emission will replicate the signatures implied by $\gamma\gamma \rightarrow e^+e^-$ attenuation. The diagnostic capability of existing telescopes to address these issues may actually be superseded by lower threshold instruments such as STACCE and CELESTE, which will feature prominently in the near future given that (i) they probe a key portion of the burst spectral range, and (ii) their sensitivity (and angular resolution) betters that of GLAST (their principal competitor) above around 10 GeV. One very nice aspect of this problem is that multi-wavelength observations will maximize the improvement of our understanding of bursts, involving techniques ranging from the ground-based TeV variety that was the focus of this conference, space-based hard and soft gamma-ray detectors, and X-ray telescopes such as that which turned the GRB field around this year. It is anticipated that the TeV gamma-ray astronomy community will be active participants in elucidating the gamma-ray burst mystery in the future.

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