Gamma Ray Bursts as Possible High Energy Sources

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Gamma-ray bursts are known to be sources of high-energy γ rays, and are likely to be sources of high-energy cosmic rays and neutrinos. Following a short review of observations of GRBs at multi-MeV energies and above, the physics of leptonic and hadronic models of GRBs is summarized. Evidence for two components in BATSE and EGRET/TASC data suggest that GRBs are sources of high-energy cosmic rays. GLAST observations will reveal the high-energy γ-ray power and energy releases from GRBs, and will provide detailed knowledge of anomalous high-energy emission components, but confirmation of cosmic ray acceleration must await 100 TeV – PeV neutrino detection from GRBs.

1 Introduction

Gamma-ray burst (GRB) studies represent one of the most dynamic fields in contemporary astronomy, and the field continues to evolve rapidly as new instrumentation comes online. Knowledge of GRBs in the high-energy, multi-MeV regime is poised to undergo great advances in the near future. Right now, Swift is exploring the late prompt and early afterglow phases of GRBs at X-ray and hard X-ray energies with unprecedented detail. The ground-based air Cherenkov telescopes, including HESS, VERITAS, and MAGIC, are reaching better sensitivities and lower thresholds with the goal of detecting GRBs at \( \sim 100 \) GeV – TeV energies. The MAGIC telescope has already demonstrated the ability to slew within \( \approx 30 \) s to a GRB. AGILE, a small scientific mission developed by the Italian Space Agency, is due for launch next year. With sensitivity comparable to EGRET, though with a much larger field-of-view (factor-of-two decline in sensitivity at an off-axis angle of \( \sim 60^\circ \), versus \( \sim 25^\circ \) for EGRET), it should detect some 5 – 10 GRBs per year above 100 MeV. The GLAST mission, which includes both the Gamma-ray Burst Monitor and Large Area Telescope that will cover energies from \( \approx 5 \) keV and above, is scheduled for launch in September 2007. Its peak effective area at \( \approx 1 \) GeV will be \( \approx 8 \times \) greater than EGRET’s at \( \approx 100 \) MeV, and its field-of-view represents \( \approx 1/6^{th} \) of the full sky, compared to \( \approx 1/20^{th} \) for EGRET. This should lead to the detection of some 30 – 100 GRBs per year at \( \gtrsim 100 \) MeV energies.
Beyond the electromagnetic realm, there is the real possibility that GRBs will be the first detected sources of high-energy ($\gg 1$ TeV) neutrinos. The south pole AMANDA neutrino detector is, as new strings are added, evolving into the km$^3$ IceCube neutrino telescope over the course of this decade. AMANDA has already detected thousands of cosmic-ray induced background neutrinos events, and improved sensitivity and background rejection should soon reveal meaningful upper limits on GRB source models if not direct detections. If GRBs are sources of ultra-high energy cosmic rays (UHECRs), then detection of $\gtrsim 10^{17}$ eV neutrino coincident with GRBs may be possible with Auger and ANITA. In view of the rapid technological advances expected over the next 5 years, therefore, we can expect that our knowledge of GRBs as high-energy sources will vastly increase.

In this contribution, I summarize what is now known from observations of high-energy radiation from GRBs. This includes primarily the Compton Gamma Ray Observatory results, which have provided the most significant detections of multi-MeV emission from GRBs. An important result from EGRET is that there is good evidence for two components in GRBs, and incontrovertible evidence for an extended phase, as observed from GRB 940217. In addition, an anomalous $\gamma$-ray emission component was detected from GRB 941017. There is, moreover, a tantalizing suggestion of TeV emission from GRB 970417a, made with the Milagrito telescope.

Interpretation of these results is made within the blast-wave scenario, which was originally developed to understand GRB afterglows [1]. Although normally used to model leptonic afterglow emissions from GRBs, this scenario can also be used to predict emission signatures from hadrons accelerated by GRBs. If GRBs accelerate UHECRs, then anomalous $\gamma$-ray emission signatures are expected from GRBs. Studies of high-energy radiation from GRBs have the potential to answer one of the outstanding questions in contemporary astronomy, namely the origin of the cosmic rays. Detection of $\gtrsim 10^{14}$ eV neutrinos from GRBs would provide compelling evidence in support of this solution.

2 Observations of High Energy Radiation from GRBs

The Solar Maximum Mission satellite revealed that $\gtrsim 1$ MeV emission was a common property of GRBs [2], thus establishing that the radiation has a nonthermal origin. COMPTEL detected over 30 GRBs at photon energies $E > 0.75$ MeV [3]. The spark chamber on EGRET detected $\gtrsim 30$ MeV photons from 7 GRBs [4]. These GRBs are invariably among the most fluent BATSE bursts, indicating that detection of $\gtrsim 100$ MeV emission is sensitivity-limited rather than a property of some subset of long-duration GRBs. The average photon spectral index of four EGRET GRBs (which includes GRB 940217), consisting of 45 photons with $E > 30$ MeV,
is \(\langle \alpha \rangle = 1.95 \pm 0.25\), consistent with being a high-energy extension of the spectrum observed with BATSE.

Fig. 1 shows the light curve and spectra of the famous burst GRB 940217, which displayed an Earth-occulted \(\sim 100\) MeV tail that lasted for \(\sim 95\) minutes, two \(\sim 3\) GeV photons during the 180 s time interval when the BATSE emission was detected, and an 18 GeV photon 90 minutes later [5]. The total number of spark chamber events was 28, with 10 photons observed during the first 180 s, and another 10 after Earth occultation. The total > 20 keV fluence of this event over the BATSE energy range was \(\gtrsim 6.6 \times 10^{-4}\) ergs cm\(^{-2}\).

The interval 1 and 2 \(\nu F_\nu\) spectra are shown in the inset. The interval 1 spectrum clearly shows a second component rising in the 100 MeV – GeV range with no evidence of a cutoff. Even during interval 2, which lasted for 5,400 s following the 180 s GRB, there is evidence from the EGRET Total Absorption Shower Counter (TASC) and spark chamber for two distinct components. The TASC, which measured spectra in the \(\sim 1 – 200\) MeV range and served as a calorimeter to measure total photon energies for EGRET, detected at least 26 GRBs [6, 7]. Joint analysis [7] of the BATSE Large Area Detector (LAD) and the EGRET TASC data resulted in the detection of an anomalous MeV emission component in the spectrum of GRB 941017 that decays more slowly than the prompt emission detected with the LAD in the \(\approx 50\)
keV – 1 MeV range. The multi-MeV component lasted for \( \gtrsim 200 \) seconds (the \( t_{90} \) duration of the lower-energy prompt component was 77 sec), and was detected with the LAD near 1 MeV and with the TASC between \( \approx 1 \) and 200 MeV. The spectrum is very hard, with a photon number flux \( \phi(E) \propto E^{-1} \). Anomalous emission components have now been detected in at least two other GRBs (M. M. González and B. L. Dingus, private communication, 2004).

At TeV energies, analysis [8] of data from the all-sky water Cherenkov telescope Milagrito correlated with the times of 54 BATSE GRBs within its field of view resulted in one statistically significant excess, namely GRB 970417a. This BATSE GRB had a relatively low fluence of \( \approx 1.5 \times 10^{-7} \) ergs cm\(^{-2} \) at 50 – 300 keV energies, and a \( \nu F_\nu \) peak energy \( E_{\text{pk}} \) below the BATSE energy band, so that it would technically be described as an X-ray flash or X-ray rich GRB. Besides needing to be relatively nearby (redshift \( z \lesssim 0.2 \)) to avoid strong attenuation on the diffuse intergalactic infrared radiation field, its TeV fluence would have to be at least an order of magnitude greater than the BATSE fluence, i.e., \( \gtrsim 10^{-6} \) ergs cm\(^{-2} \), to be detected with Milagrito.

No evidence for high-energy neutrinos coincident with GRBs has yet been reported with the AMANDA array [9].

3 Models for High Energy \( \gamma \) Rays from GRBs

We consider both leptonic and hadronic models for emissions from GRBs, focusing on the particular cases of GRB 940217, GRB 970417a, and GRB 941017.

3.1 GRB 940217

The discovery of the extended phase of emission from GRB 940217 took place prior to the confirmation that GRBs originate from cosmological distances. Even now, however, there is no agreed explanation for this high-energy radiation. An early model by Katz [10] argued that collisions of cosmic rays with gas in a dense clouds produced secondary \( \pi^0 \) radiation. This model cannot possibly be valid for a source at cosmological distances, given the required energies and decay time scale. A second early model, by Mészáros and Rees [11], is sketched within the context of a relativistic outflow from a cosmological source. Here, the delayed emission is due either to successive waves of ejecta that collide at later times, or in terms of relativistic ejecta being slowed by the external medium to form GeV radiation. With the suggestion that UHECRs are accelerated by GRB blast waves [12] [13], it was recognized that cascade radiation signatures of UHECRs interacting with photons of the microwave background could produce GeV–TeV photons [14]. This could not, however, account
Figure 2: Calculations of SEDs from uncollimated GRB blast waves that are energized, decelerate and radiate by capturing material from a uniform surrounding medium; parameters are described in the text. The initial Lorentz factor $\Gamma_0 = 100$ and $\Gamma_0 = 300$ in the left and right panels, respectively. The $\nu L_\nu$ SEDs are shown at observer times of $10^j$ seconds after the onset of the GRB event, with $j$ given in the captions.

for the emission from GRB 940217, which is correlated with peaks in the BATSE emission during the prompt phase, and decays on a much shorter timescale than would occur from cascade processes involving diffuse intergalactic radiation.

Progress in the development of the blast-wave model of GRBs permitted a quantitative application of this model to observations of high-energy radiation from GRBs. Using a numerical simulation code developed by J. Chiang [15], the synchrotron and synchrotron self-Compton (SSC) emissions in a leptonic blast wave model were modeled, giving the results shown in Fig. 2. In addition to synchrotron and SSC processes, the numerical simulation model [16] includes synchrotron self-absorption and adiabatic loss processes, and follows blast-wave evolution self-consistently. The photons are attenuated by internal $\gamma\gamma$ absorption, but pair reinjection is not followed.

In this calculation, we consider an external shock model for a GRB taking place in a uniform surrounding medium with density $n_0 = 100$ cm$^{-3}$. The GRB is assumed to produce a thin blast wave where only the forward shock produces strong particle acceleration and radiation. The apparent isotropic explosion energy of the GRB is $10^{54}$ ergs, and the fraction $\epsilon_e$ of nonthermal swept-up proton kinetic energy transferred to nonthermal electrons is 0.5, the injection index $p = 2.5$ for the electrons, and $\epsilon_B = 10^{-4}$, where the comoving magnetic field strength $B$ is defined by the relation $B^2/8\pi = 4\epsilon_B\Gamma^2m_pc^2n_0$. The maximum electron Lorentz factor is determined by the value where the gyration timescale equals the synchrotron energy-loss timescale. Fig. 2 shows temporally evolving $\nu L_\nu$ spectra for an uncollimated blast wave with
two values of $\Gamma_0$. The microscopic parameters are assumed to be time-independent. In both calculations, the SSC process makes a distinct component that rises at multi-GeV energies to produce emission at TeV energies before being attenuated by internal absorption. The $\gamma\gamma$ process degrades only $\gtrsim 1$ TeV photons in the models shown here. Thus the internal attenuation of high-energy gamma rays is not too severe and the SSC component is bright enough that TeV radiation is produced at a comparable $\nu F_\nu$ level as the synchrotron radiation. By studying the temporal dependence of the $\sim$ GeV radiation in the $\Gamma_0 = 300$ case, one sees that because of the deceleration of the blast wave, the SSC flux sweeping through the EGRET band could in principle make an emission component over a few thousand seconds that would decay much more slowly than the X-ray and MeV emissions. We proposed [16] that this was the origin of the extended emission component in GRB 941017. Careful examination of the numerical simulation result for the $\Gamma_0 = 300$ case shows, however, that there is at least a one-to-two order-of-magnitude decline in the GeV flux over the first several thousand seconds. Suitable choice of parameters, for example, by reducing the maximum electron energy, could make a relatively constant $\approx 100$ MeV – GeV flux for an hour or two, so this model provides a viable explanation for the delayed emission from GRB 941017.

3.2 GRB 970417a

The lower Lorentz factor (“dirty fireball”) case with $\Gamma_0 = 100$ in Fig. 2 produces a larger relative $\nu F_\nu$ flux in the SSC component than in the synchrotron component and, moreover, produces the $E_{pk}$ value of the synchrotron component at keV rather than MeV energies. The TeV radiation detected by Milagro from GRB 970417a could originate from the SSC emission from a nearby $z \lesssim 0.2$ GRB [16]. Although the leptonic blast wave model is consistent with observations of the TeV emission from GRB 970417a, other explanations are possible, including proton synchrotron radiation [17]. This alternative would require very strong magnetic fields in the GRB blast waves, with energy requirements that may be unacceptable. Another important issue that will arise if TeV emission is confirmed from GRBs is whether such emission is compatible with an internal shock model. The $\gamma\gamma$ absorption at TeV emission is very large unless the bulk Lorentz factors $\Gamma_0$ of the outflows exceed several hundreds [18].

3.3 GRB 941017

In contrast, an external shock model with strong forward shock emission does not easily explain the anomalous $\gamma$-ray emission component from GRB 941017. It has been proposed that within the standard leptonic blast-wave model, this separate component
could be reverse-shock emission Compton-scattered by the forward shock electrons [19], including self-absorbed reverse-shock optical synchrotron radiation [20]. This latter model requires very large apparent isotropic energies exceeding $10^{54}$ ergs, and forward and reverse shock microphysical parameters that are very different. Another possibility is that hadronic acceleration in GRB blast waves could be responsible for this component.

We have argued [21] that the anomalous $\gamma$-ray emission component in GRB 941017 could be a consequence of the acceleration of hadrons at the relativistic shocks of GRBs. A pair-photon cascade initiated by photohadronic processes between high-energy hadrons accelerated in the GRB blast wave and the internal synchrotron radiation field produces an emission component that appears during the prompt phase, as shown in Fig. 3. Photomeson interactions in the relativistic blast wave also produce a beam of UHE neutrons, as proposed for blazar jets [22]. Subsequent photopion production of these neutrons with photons outside the blast wave will produce a directed hyper-relativistic electron-positron beam in the process of charged pion decay and the conversion of high-energy photons formed in $\pi^0$ decay. These energetic leptons produce a synchrotron spectrum in the radiation reaction-limited regime extending to $\gtrsim$ GeV energies, with properties in the 1 – 200 MeV range similar to that measured from GRB 941017. GRBs displaying these anomalous $\gamma$-ray components are most likely to be detected as sources of high-energy neutrinos [23].

A hadronic origin for high-energy $\gamma$-ray emission components is also attractive in view of the extended phase of high-energy radiation from GRB 940217. This is because hadronic secondary radiation decays more slowly than leptonic emission,
primarily due to the less efficient cooling of protons than electrons [24]. A proton synchrotron model faces, however, severe difficulties because of the large field and particle energies required to accelerate protons to sufficiently high energies where this process becomes important. On the other hand, protons which radiate via photo-meson processes require dense internal radiation fields that produce strong attenuation at GeV – TeV energies. A leptonic origin is more probable if γ-ray fluxes extending smoothly to ≫ GeV energies is observed. If strong anomalous components showing strong γγ attenuation cutoff at energies ≳ 100 MeV – few GeV are observed, as in Fig. 3, then this will provide strong evidence for hadronic acceleration by GRBs. AGILE and GLAST will therefore provide crucial evidence to distinguish the leptonic and hadronic origins of high-energy γ-ray emissions in GRBs. An inverse correlation is expected between neutrino detection and γ-ray detection, because a strong internal radiation field, and therefore also strong γγ absorption, is required for efficient high-energy neutrino production [25, 13].

4 Cosmic Rays and Neutrinos from GRBs

Because high-energy γ rays are emitted by GRBs, high-energy particles must be accelerated by GRB blast waves. GRBs provide a very attractive solution to the origin of high-energy cosmic rays (HECRs; ≳ 10^{14} eV) ranging from below the knee of the cosmic-ray spectrum to the highest energies exceeding 10^{20} eV. For instance, the luminosity density in γ radiation is comparable to the power required to accelerate super-GZK cosmic rays with energies exceeding ≲ 6 × 10^{19} eV [12, 13]. GRBs are associated with Type 1c supernovae, and are therefore related to the most probable accelerators of GeV – TeV cosmic rays, namely supernovae of all types. GRBs are found both in our Galaxy and throughout the universe; thus they can account for cosmic rays with energies between ≈ 10^{14} eV and ≈ 5 × 10^{17} eV due to GRBs in our Galaxy, and for metagalactic UHECRs due to extragalactic GRBs [26]. We have recently argued that HECRs originate from galactic and extragalactic GRBs [26]. In our model, relativistic outflows in GRBs are assumed to inject power-law distributions of cosmic rays to the highest ( ≳ 10^{20} eV) energies. A diffusive propagation model for HECRs from a single recent GRB within ≈ 1 kpc from Earth that took place within the last 0.5 million years explains the KASCADE data for the cosmic-ray ion spectra near and above the knee. The cosmic-ray spectrum at energies above the second knee at ≈ 10^{17.6} eV is fit with CRs from extragalactic GRBs. UHECRs produced by extragalactic GRBs lose energy from momentum redshifting. Attenuation features in the UHECR flux are produced at characteristic energies ≈ 4 × 10^{18} eV and ≈ 5 × 10^{19} eV due to photo-pair and photo-pion energy-loss processes, respectively.
A fit to the combined KASCADE, HiRes-I and HiRes-II monocular data between \(\approx 8 \times 10^{14} \text{eV}\) and \(3 \times 10^{20} \text{eV}\) is shown in Fig. 4, with a cosmic-ray number injection index \(\beta = 2.2\), an exponential cutoff energy of \(E_{\text{max}} = 10^{20} \text{eV}\), and a star-formation rate history of GRBs which is larger than that inferred from the blue-UV luminosity density. The cutoff energy for the galactic-halo component is \(E_{\text{halo max}} = \text{10}^{17.07} \text{eV}\). The transition between galactic and extragalactic CRs is found in the vicinity of the second knee at \(\approx \text{10}^{17.6} \text{eV}\), consistent with a heavy-to-light composition change at this energy. The ankle, at \(\approx \text{10}^{18.5} \text{eV}\), is interpreted as a suppression from photo-pair losses \([27]\), analogous to the GZK suppression.

By normalizing the energy injection rate to that required to produce the CR flux from extragalactic sources observed locally, we determine the amount of energy a typical GRB must release in the form of nonthermal hadrons. Our results imply that GRB blast waves are baryon-loaded by a factor \(f_{\text{CR}} \approx 60\) compared to the primary electron energy that is inferred from the fluxes of hard X-rays and soft \(\gamma\) rays measured from GRBs. For the large baryon load required for the proposed model of HECRs, calculations show that 100 TeV – 100 PeV neutrinos could be detected several times per year from all GRBs with kilometer-scale neutrino detectors such as IceCube \([25,26]\). Detection of even 1 or 2 neutrinos from GRBs with IceCube or a northern hemisphere neutrino detector will provide compelling support for this scenario for the origin of high-energy and UHE cosmic rays.

If GRBs are the sources of HECRs, then high-energy neutrons will be formed at the burst site through photo-pion processes and, being neutral, can escape to in-
tergalactic space. The decay of the neutrons far from the GRB through the process $n \rightarrow p + e^- + \nu_e$ leads to \(\beta\)-decay electrons that make weak synchrotron and Compton radiation. The best prospect for discovering neutron-decay halos is to search for diffuse optical synchrotron halos surrounding field galaxies that display active star formation [28]. GRBs that have recently taken place in our Galaxy will produce Compton emissions at TeV energies that could be detected by the HESS and VERITAS imaging air Cherenkov telescopes [29]. Nonthermal synchrotron and Compton radiations produced by secondaries formed in photopion processes by UHECRs traveling through intergalactic space will also form a nonthermal component of the diffuse radiation background, which can be used to measure the magnetic field of intergalactic space.

Because the Milky Way is actively making young high-mass stars, GRBs will also occur in our Galaxy. The rate of GRBs in the Milky Way is very uncertain because of lack of precise knowledge about the opening angle of GRB jets, but could be as frequent as once every 10,000 years. Over the age of the Galaxy, there is a good chance that a nearby powerful GRB with a jet oriented towards Earth could have lethal consequences for life. It has recently been argued [30] that such an event contributed to the Ordovician extinction event 440 Myrs ago. UHECRs accelerated by galactic cosmic rays will produce an additional radiation hazard [31], though we predict that GRBs cannot produce point-sources of UHECRs.

5 Conclusions

GRBs are established to be sources of high-energy \(\gamma\) rays. Here we have argued GRBs also accelerate hadrons, and that GRBs are sources of high-energy cosmic rays. Evidence for this is suggested by the slow decay of \(\gamma\) rays from GRB 941017, and by the anomalous \(\gamma\)-ray emission component in GRB 941017.

Several types of observations can test this hypothesis. Most unambiguous is the detection of high-energy neutrinos from a GRB, which would require an ultrarelativistic hadronic component that is much more powerful than the nonthermal electron component that produces the hard X-ray and soft \(\gamma\)-ray emissions from GRBs [25]. Another prediction is the detection of hadronic emission components in the spectra of GRBs, as observed in GRB 941017 [2]. A third observation that would implicate GRBs as the sources of HECRs is the detection of high-energy neutron \(\beta\)-decay halos around star-forming galaxies [28], including \(\beta\)-decay emission from GRBs in the Milky Way [29].

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