High Energy Photons, Neutrinos and Gravitational Waves from Gamma-Ray Bursts

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1 Introduction

A new era in Gamma-ray Burst (GRB) research opened in 1991 with the launch of the Compton Gamma-Ray Observatory (CGRO), whose ground-breaking results have been summarized in [1]. The most significant results came from the all-sky survey by the Burst and Transient Experiment (BATSE) on CGRO, which recorded over 2700 bursts, complemented by data from the OSSE, Comptel and EGRET experiments, in the 20 keV - 1 MeV, 0.1-10 MeV, 1-30 MeV and 20 MeV - 30 GeV gamma-ray bands, respectively. The next major advance was ushered in by the Italian-Dutch satellite Beppo-SAX in 1997, which obtained the first high resolution 0.2-10 keV x-ray images [2] of the fading afterglow of a burst, GRB 970228, a phenomenon which had been previously theoretically predicted. This was followed by an increasing list of burst afterglow detections with Beppo-SAX. These X-ray detections, after a 4-6 hour delay needed for data processing, led to arc-minute accuracy positions, which finally made possible the optical detection and the follow-up of the GRB afterglows at longer wavelengths (e.g. [3, 4]). This paved the way for the measurement of redshift distances, the identification of candidate host galaxies, and the confirmation that they were at cosmological distances [5, 6], etc. In the last year, the HETE-2 spacecraft [7] has been discovering bursts at the rate of \( \sim 2/\text{month} \), in the 0.5-400 keV range. Besides classical bursts, a number of these have been in the sub-class of X-ray flashes, first identified with Beppo-SAX [8], or X-ray rich bursts [9].

Another remarkable observation [10] was that of a prompt and extremely bright \( (m_v \sim 9) \) optical flash in the burst GRB 990123, 15 seconds after the GRB started (and while it was still going on). A prompt multi-wavelength flash, contemporaneous with the \( \gamma \)-ray emission and reaching such optical magnitude levels is an expected consequence of the reverse component of external shocks [11, 12]. The prompt optical flash of 990123 is generally interpreted [13, 14] as the radiation from a reverse external shock (although prompt optical flashes can be expected from both an external reverse shock and from an internal shock [12]). The behavior of the reverse shock is
more sensitive than the forward shock on the details of the shock physics \[15\]. This
has become apparent with the recent prompt flashes seen from ground-based optical
follow-up of two other bursts, GRB 021004 and GRB 021211, \[16, 17, 18\], made
possible by HETE-2 spacecraft position alerts. In the near future, the prospects
look bright for detecting 100-150 bursts per year with a new multi-wavelength GRB
follow-up spacecraft called Swift \[19\], which is due for launch in December 2003 and
is equipped with γ-ray, x-ray and optical detectors. Predictions of the dependence of
spectra and lightcurves on the initial bulk Lorentz factor, magnetic energy content,
etc. \[20\] opens up the interesting possibility of charting in much greater detail the
shock physics and the dynamics of the relativistic outflow in GRB.

The large bulk of the information on GRB has come from electromagnetic signals
at MeV and lower energies, except for a handful of bursts detected at higher photon
energies with SMM \[21\], with the EGRET, OSSE and Comptel experiments on CGRO
\[1\], and more recently INTEGRAL \[22\]. However, new missions are planned for ultra-
high energies (UHE). One of these, aimed at the 20 MeV - 300 GeV as well as as
10 keV - 30 MeV range, is GLAST \[23\], due for launch in 2006. In addition, several
new ground-based air and water Cherenkov telescopes as well as solar array facilities
are coming or will shortly come on-line, sensitive in the 0.2-10 TeV range, with GRB
as one possible class of targets \[24\]. Furthermore, there are several other, as yet
unconfirmed, but potentially interesting observing channels for GRBs, relating to the
baryonic component of the outflow, the shock physics and the progenitor collapse
dynamics. There is the prospect of measuring ultra-high energy cosmic rays from
GRB with the Auger array \[25\]; TeV and higher energy neutrinos with large, cubic
kilometer ice or water Cherenkov telescopes such as ICECUBE or ANTARES \[26\]; and
measuring gravitational wave signals accompanying the GRB formation with LIGO
and similar arrays \[27\]. We discuss below some of the theoretical expectations for
the GRB ultra-high energy (UHE) \(\gtrsim\) GeV electromagnetic signals, the UHE neutrino
signals, and the gravitational wave signals.

2 UHE photons from GRB

Ultra-high energy emission, in the range of GeV and harder, is expected from from
electron inverse Compton in external shocks \[28\] as well as from internal shocks
\[29\] in the prompt phase. The combination of prompt MeV radiation from internal
shocks and a more prolonged GeV IC component for external shocks \[30\] is a likely
explanation for the delayed GeV emission seen in some GRB \[31\]. (For an alternative
invoking photomeson processes from ejecta protons impacting a nearby binary stellar
companion see \[32\]). The GeV photon emission from the long-term IC component in
external afterglow shocks has been considered by \[33, 34, 35\]. The IC GeV photon
component is likely to be significantly more important \[33\] than a possible proton
synchrotron or electron synchrotron component at these energies. Another possible contributor at these energies may be $\pi^0$ decay from $p\gamma$ interactions between shock-accelerated protons and MeV or other photons in the GRB shock region \cite{36, 37, 38}. However, under the conservative assumption that the relativistic proton energy does not exceed the energy in relativistic electrons or in $\gamma$-rays, and that the proton spectral index is -2.2 instead of -2, both the proton synchrotron and the $p\gamma$ components can be shown to be substantially less important at GeV-TeV than the IC component \cite{33}. Another GeV photon component is expected from the fact that in a baryonic GRB outflow neutrons are likely to be present, and when these decouple from the protons, before any shocks occur, $pn$ inelastic collisions will lead to pions, including $\pi^0$, resulting in UHE photons which cascade down to the GeV range \cite{39, 40}. The final GeV spectrum results from a complex cascade, but a rough estimate indicates that 1-10 GeV flux should be detectable with GLAST for bursts at $z \lesssim 0.1$ \cite{40}.

**Figure 1:** *Left panel:* Parameter regimes for GRB GeV emission dominated by proton synchrotron (I), electron synchrotron (III) and electron inverse Compton (II). *Right panel:* GeV lightcurves for the three types of bursts in the range 400 MeV - 200 GeV. The solid curves indicate bursts in regimes I (p-sy), II (e-IC) and III (e-sy), at a distance $z = 1$. The three dotted unmarked curves are the same but located at $z = 0.1$. Also shown are the sensitivity curves for *EGRET* and *GLAST*.

In these models, due to the high photon densities implied by GRB models, $\gamma\gamma$ absorption within the GRB emission region must be taken into account (see also \cite{41, 42}). So far, these calculations have been largely analytical. One interesting result is that the observation of photons up to a certain energy, say 10-20 GeV with *EGRET*, puts a lower limit on the bulk Lorentz factor of the outflow, from the fact that the compactness parameter (optical depth to $\gamma\gamma$) is directly proportional to the
comoving photon density, and both this as well as the energy of the photons depend on the bulk Lorentz factor. This has been used by [42] to estimate lower limits on $\Gamma$ in the range 300-600 for a number of specific bursts observed with EGRET.

At higher energies, a tentative $\gtrsim 0.1$ TeV detection at the $3\sigma$ level of GRB970417a has been reported with the water Cherenkov detector Milagrito [43]. Another possible TeV detection [44] of GRB971110 has been reported with the GRAND array, at the $2.7\sigma$ level. Stacking of data from the TIBET array for a large number of GRB time windows has led to an estimate of a $\sim 7\sigma$ composite detection significance [45]. Better sensitivity is expected from the upgraded larger version of MILAGRO, as well as from atmospheric Cherenkov telescopes under construction such as VERITAS, HESS, MAGIC and CANGAROO-III [24]. However, GRB detections in the TeV range are expected only for rare nearby events, since at this energy the mean free path against $\gamma\gamma$ absorption on the diffuse IR photon background is $\sim$ few hundred Mpc [46, 47]. The mean free path is much larger at GeV energies, and based on the handful of GRB reported in this range with EGRET, several hundred should be detectable with large area space-based detectors such as GLAST [23, 33].

3 UHE neutrinos from GRB

While stellar scenarios for GRB will result in large thermal ($\sim 10-30$ MeV) neutrino luminosities comparable to those in supernovae, at typical redshifts $z \sim 1$ these are extremely hard to detect due to the low cross sections at these energies. However, the neutrino detection cross section increases with energy, and near TeV energies there are realistic chances for detection [26] with cubic kilometer ice or water Cherenkov detectors, such as the planned ICECUBE or ANTARES.

A mechanism leading to higher (GeV) energy neutrinos in GRB is inelastic nuclear collisions. Proton-neutron inelastic collisions are expected, at much lower radii than where shocks occur, due to the decoupling of neutrons and protons in the fireball or jet [48]. If the fireball has a substantial neutron/proton ratio, as expected in most GRB progenitors, the collisions become inelastic and their rate peaks at when the nuclear scattering time becomes comparable to the expansion time. This occurs when the $n$ and $p$ fluids decouple, their relative drift velocity becoming comparable to $c$, which is easier due to the lack of charge of the neutrons. Inelastic $n,p$ collisions then lead to charged pions and GeV muon and electron neutrinos [49]. The early decoupling and saturation of the $n$ also leads to a somewhat higher final $p$ Lorentz factor [48, 49, 50, 51], implying a possible relation between the $n/p$ ratio and the observable fireball dynamics, relevant for the progenitor question. Fusion and photodisociation processes also play a role in such effects [52, 53]. Inelastic $p,n$ collisions leading to neutrinos can also occur in fireball outflows with transverse inhomogeneities in the bulk Lorentz factor, where the $n$ can drift sideways into regions of different bulk velocity flow, or
in situations where internal shocks involving $n$ and $p$ occur close to the saturation radius or below the photon photosphere [51]. The typical $n, p$ neutrino energies are in the 1-10 GeV range, which could be detectable in coincidence with observed GRBs for a sufficiently close photo-tube spacing in km$^3$ detectors such as ICECUBE [19].

Neutrinos at energies $\gtrsim 100$ TeV are expected from $p, \gamma$ photo-pion interactions between relativistic protons accelerated in the fireball internal or external shocks. A high collision rate is ensured here by the large density of photons in the fireball shocks. The most straightforward is the interaction between MeV photons produced by radiation from electrons accelerated in internal shocks and relativistic protons accelerated by the same shocks [55], leading to charged pions, muons and neutrinos. This $p, \gamma$ reaction peaks at the energy threshold for the photo-meson $\Delta$ resonance in the fluid frame moving with $\gamma$, or $\epsilon_p \epsilon_\gamma \gtrsim 0.2 \text{GeV}^2 \gamma^2$. For observed 1 MeV photons this implies $\gtrsim 10^{16}$ eV protons, and neutrinos with $\sim 5\%$ of that energy, $\epsilon_\nu \gtrsim 10^{14}$ eV in the observer frame. Above this threshold, the fraction of the proton energy lost to pions is $\sim 20\%$ for typical fireball parameters, and the typical spectrum of neutrino energy per decade is flat, $\epsilon_\nu^2 \Phi_{\nu} \sim \text{constant}$. Synchrotron and adiabatic losses limit the muon lifetimes [56], leading to a suppression of the neutrino flux above $\epsilon_\nu \sim 10^{16}$ eV. In external shocks another copious source of targets are the O/UV photons in the afterglow reverse shock (e.g. as deduced from the GRB 990123 prompt flash of [10]). In this case the resonance condition implies higher energy protons, leading to neutrinos of $10^{17} - 10^{19}$ eV [57, 58]. These neutrino fluxes are expected to be detectable above the atmospheric neutrino background with the planned cubic kilometer ICECUBE detector [26]. Useful limits to their total contribution to the diffuse ultra-high energy neutrino flux can be derived from observed cosmic ray and diffuse gamma-ray fluxes [59, 60, 61]. While the $p, \gamma$ interactions leading to $\gtrsim 100$ TeV energy neutrinos provide a direct probe of the internal shock acceleration process, as well as of the MeV photon density associated with them, the $\gtrsim 10$ PeV neutrinos would probe the reverse external shocks, as well as the photon energies and energy density there.

The most intense neutrino signals may be due to $p, \gamma$ interactions occurring inside collapsars while the jet is still burrowing its way out of the star [62], before it has had a chance to break through (or not) the stellar envelope to produce a GRB outside of it. While still inside the star, the buried jet produces thermal X-rays at $\sim 1$ keV which interact with $\gtrsim 10^5$ GeV protons which could be accelerated in internal shocks occurring well inside the jet/stellar envelope terminal shock, producing $\gtrsim$ few TeV energy neutrinos for tens of seconds, which penetrate the envelope. The most conspicuous contribution of TeV $\nu_\mu$ is due to $pp, pn$ collisions involving the buried jet relativistic protons and thermal nucleons in the jet and the stellar envelope [63], while $p\gamma$ is important at higher energies $\gtrsim 100 TeV$. At TeV energies the number of neutrinos is larger for the same total energy output, which improves the detection statistics. The rare bright, nearby or high $\gamma$ collapsars could occur at the rate of $\sim 10$/year,
including both γ-ray bright GRBs (where the jet broke through the envelope) and γ-ray dark events where the jet is choked (failed to break through), and both such γ-bright and dark events could have a TeV neutrino fluence of \( \sim 10/\text{neutrinos/burst} \), detectable by ICECUBE in individual bursts.

Figure 2: Left panel: The diffuse muon-neutrino flux \( E_\nu^2 \Phi_\nu \varepsilon_{\text{op}}^{-1} \) is shown as solid lines for \( \nu_\mu \) from sub-stellar jet shocks in two GRB progenitor models, \( r_{12.5} \) (H) and \( r_{11} \) (He). These neutrinos arrive as precursors (10-100 s before) of γ-ray bright (electromagnetically detectable) bursts. Also shown is the diffuse neutrino flux arriving simultaneously with the γ-rays from shocks outside the stellar surface in observed GRB (dark short-dashed curve); the Waxman-Bahcall (WB) diffuse cosmic ray bound (light long-dashed curves); and the atmospheric neutrino flux (light short-dashed curves). For a hypothetical 100:1 ratio of γ-ray dark (in which the jets do not emerge) to γ-ray bright collapses, the solid neutrino spectral curves would be 100 times higher. Right panel: Diffuse neutrino flux \( E_\nu^2 \Phi_\nu \) from post-supernova (supra-nova) models of GRBs (solid curves), assuming that (top curve) all GRBs have an SNR shell, or (bottom) 10% of all GRBs have an SNR shell, and \( 10^{-1} \) of the fireball protons reach the shells. Long dashed lines correspond to the Waxman-Bahcall cosmic-ray limit, short dashed curves are the diffuse \( \nu \) flux from GRB internal shocks and afterglows.

Recent reports of detection of X-ray lines from several GRB afterglows have been interpreted \[61\], although not unambiguously, as providing support for a version of the collapsar model in which a SN explosion occurs weeks before the GRB (the “supra-nova” model, \[65\]). In the supranova scenario the supernova remnant (SNR) shell provides nucleon targets for \( pp \) interactions with protons accelerated in the MHD wind of a pre-GRB pulsar \[66\], leading to a 10 TeV neutrino precursor to the GRB (other nucleon targets from a stellar companion disruption leading to \( \pi^0 \) decay GeV γ-rays were discussed by \[32\]). The SNR also provides additional target photons for \( p\gamma \) interactions \[66\] with internal shock-accelerated protons, resulting in \( \sim 10^{16} \) eV
neutrinos. We have calculated the expected neutrino fluxes and muon event rates from individual bursts as well as the diffuse contribution from all bursts \[67\]. The neutrinos produced by $pp$ and $p\gamma$ interactions between GRB relativistic protons and SNR shell target protons and photons will be contemporary and of similar duration as the GRB electromagnetic event. The high $pp$ optical depth of the shell also implies a moderately high average Thomson optical depth $\tau_T \propto t_d^{-2}$ of the shell, dropping below unity after $\sim 100$ days. Large scale anisotropy as well as clumpiness of the shell will result in a mixture of higher and lower optical depth regions being observable simultaneously, as required in the supranova interpretation of X-ray lines and photon continua in some GRB afterglows \[64\]. Depending on the fraction of GRB with SNR shells, the contributions of these to the GRB diffuse neutrino flux has a $pp$ component which is relatively stronger at TeV-PeV energies than the internal shock $p\gamma$ component of \[55\], and a shell $p\gamma$ component which is a factor 1 (0.1) of the internal shock $p\gamma$ component (Fig. 2) for a fraction 1 (0.1) of GRB with SNR shells. Due to a higher synchrotron cooling break in the shell, at $E_\nu > \sim 10^{17}$ eV the shell component could compete with the internal \[55\] and afterglow \[57\] components. Our $pp$ component is caused by internal shock-accelerated power-law protons contemporaneous with the GRB event, differing from \[66\] who considered quasi-monoenergetic $\gamma_p \sim 10^{4.5}$ protons from an MHD wind over $4\pi$ leading to a $\sim 10$ TeV neutrino months-long precursor of the GRB. Our $p\gamma$ component arises from the same GRB-contemporaneous internal shock protons interacting with thermal 0.1 keV photons within the shell wall, whereas \[66\] consider such protons interacting with photons from the MHD wind inside the shell cavity. These neutrino fluxes provide a test for the supranova hypothesis, the predicted event rates being detectable with kilometer scale planned Cherenkov detectors.

4 Gravitational waves from GRB

The leading models for the ultimate energy source of GRB are stellar collapse or compact stellar mergers, and these are expected to be sources of gravitational waves (GWs). A time-integrated GW luminosity of the order of a solar rest mass ($\sim 10^{54}$ erg) is predicted from merging NS-NS and NS-BH models \[68\ 69\ 70\], while the luminosity from collapsar models is more model-dependent, but expected to be lower \[71\ 72\ ; c.f. \[73\]. We have estimated the strains of gravitational waves from some of the most widely discussed current GRB progenitor stellar systems \[74\]. The expected detection rates of gravitational wave events with the Laser Interferometric Gravitational Wave Observatory (LIGO) from compact binary mergers, in coincidence with GRBs, has been estimated by \[27\ 75\]. If some fraction of GRBs are produced by double neutron star or neutron star–black hole mergers, the gravitational wave chirp signal of the in-spiral phase should be detectable by the advanced LIGO within
one year, associated with the GRB electromagnetic signal. We have also estimated the signals from the black hole ring-down phase, as well as the possible contribution of a bar configuration from gravitational instability in the accretion disk following tidal disruption or infall in GRB scenarios. Other binary progenitor scenarios, such black hole – Helium star and black hole – white dwarf merger GRB progenitors are unlikely to be detectable, due to the low estimates obtained for the maximum non-axisymmetrical perturbations.

Figure 3: Left panel: Characteristic GW strains for merging double neutron stars: in-spiral (solid line), merger (dashed dotted line), bar (circle), ring-down (solid spike). Also shown is the advanced LIGO nose curve $\sqrt{fS_h(f)}$ (dashed curve). The shaded region and the vertical line reflect the uncertainty of the formation rate $R$ in Table 1. Right panel: Characteristic GW strains for collapsars: blob merger (dashed dotted line), bar (circle) and ring-down (solid spike).

For the massive rotating stellar collapse (collapsar) scenario of GRB, the non-axisymmetrical perturbations may be stronger [76, 77, 78], and the estimated formation rates are much higher than for other progenitors [77, 79], with typical distances correspondingly much nearer to Earth. This type of progenitor is of special interest, since it has so far received the most observational support from GRB afterglow observations. For collapsars, in the absence of detailed numerical 3D calculations specifically aimed at GRB progenitors, we have estimated [74] the strongest signals that might be expected in the case of bar instabilities occurring in the accretion disk around the resulting black hole, and in the maximal version of the recently proposed fragmentation scenario of the infalling core. Although the waveforms of the gravitational waves produced in the break-up, merger and/or bar instability phase of collapsars are not known, a cross-correlation technique can be used making use of two co-aligned detectors. Under these assumptions, collapsar GRB models would be
expected to be marginally detectable as gravitational wave sources by the advanced LIGO within one year of observations.

In the case of binaries the matched filtering technique can be used, while for sources such as collapsars, where the wave forms are uncertain, the simultaneous detection by two elements of a gravitational wave interferometer, coupled with electromagnetic simultaneous detection, provides a possible detection technique. We have made [74] more specific detection estimates for both the compact binary scenarios and the collapsar scenarios.

Both the compact merger and the collapsar models have in common a high angular rotation rate, and observations provide evidence for jet collimation of the photon emission, with properties depending on the polar angle, which may also be of relevance for X-ray flashes. We have considered [80] the gravitational wave emission and its polarization as a function of angle which is expected from such sources. The GRB progenitors emit \( l = m = 2 \) gravitational waves, which are circularly polarized on the polar axis, while the + polarization dominates on the equatorial plane. Recent GRB studies suggest that the wide variation in the apparent luminosity of GRBs are caused by differences in the viewing angle, or possibly also in the jet opening angle. Since GRB jets are launched along the polar axis of GRB progenitors, correlations among the apparent luminosity of GRBs \( (L_\gamma(\theta) \propto \theta^{-2}) \) and the amplitude as well as the degree of linear polarization \( P \) degree of the gravitational waves are expected, \( P \propto \theta^4 \propto L_\gamma^{-2} \). At a viewing angle larger than the jet opening angle \( \theta_j \) the GRB \( \gamma \)-ray emission may not be detected. However, in such cases an “orphan” long-wavelength afterglow could be observed, which would be preceded by a pulse of gravitational waves with a significant linearly polarized component. As the jet slows down and reaches \( \gamma \sim \theta_j^{-1} \), the jet begins to expand laterally, and its electromagnetic radiation begins to be observable over increasingly wider viewing angles. Since the opening angle increases as \( \sim \gamma^{-1} \propto t^{1/2} \), at a viewing angle \( \theta > \theta_j \), the orphan afterglow begins to be observed (or peaks) at a time \( t_p \propto \theta^2 \) after the detection of the gravitational wave burst. The polarization degree and the peak time should be correlated as \( P \propto t_p^2 \).

A new type of fast transient source, called “X-ray flashes”, have recently been observed with the Beppo-SAX satellite [9]. Apart from their large fraction of X-rays \( (\sim 2 - 10 \text{ keV}) \), the overall properties of these events are similar to those of GRBs. The nature of these sources is not yet fully understood. Although they could be a totally different astrophysical phenomenon, it has been suggested that these events may be GRBs with large viewing angles [81, 82]. If this is the case, linearly polarized gravitational waves should be observed prior to the X-ray flashes. The degree of polarization should be positively correlated with longer delays and with the softness of the X-ray flashes, which increase with angle. Since the degrees of linear and circular polarization depend on the viewing angle, a determination of the polarization degree would be a measure of the viewing angle. Such measurements, which are likely to require the advent of a future generation of detectors, could provide a new a tool
for estimating the absolute luminosity of GRBs, including its photon component. By comparing the estimated absolute photon luminosity with the apparent luminosity, the distance to the source may be estimated independently of any redshift measurement. No optical afterglows have been found for about half of all the GRBs detected by Beppo-SAX (the so called “dark GRBs”), and the present method would have the potential to help determine or constrain the distances to such dark GRBs.

PM is grateful to the Niels Bohr Institute and Nordita as well as the symposium organizers for their kind hospitality, and to NSF AST-0098416, NASA NAG5-9192 and 9153 for support.

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Discussion

A. Beloborodov (Columbia University): An additional mechanism for the high-energy break in the gamma-gamma absorption is the radiation scattered off the ambient medium. For WR-wind medium one expects a break at 10-50 MeV.

Mészáros: Yes, that is a potentially important effect, which you have discussed.

M.J. Rees (Cambridge University): The Bahcall/Waxman limit could perhaps be violated if ions were accelerated in a confined and opaque region, and didn’t escape to contribute to the cosmic ray flux. I mention this just to reduce pessimism!

Mészáros: I agree, sources which are optically thick to CRs could violate the WB limit.

T. Piran (Hebrew University): Gravitational waves can also arise from the acceleration process of the matter in GRBs.

Mészáros: This is an interesting effect, which as you discussed, would have a significantly lower flux than the main burst from mergers or core collapse.