LOCAL ABSORPTION OF HIGH-ENERGY EMISSION FROM GAMMA-RAY BURSTS

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ABSTRACT

High-energy photons emitted from gamma-ray bursts (GRBs) are subject to pair-production interactions with lower energy photons, leading to an effective optical depth. In this paper, we estimate the opacity resulting from photon fields located at various distances from long GRB sites: those of the binary companion to the massive stellar progenitor, the star-forming molecular cloud containing the GRB, and the total photon field of the host galaxy. The first two photon fields are found to be transparent for most reasonable sets of assumptions about these systems. In the case of galactic radiation fields, we have performed several numerical simulations to calculate the expected opacities for two different line-of-sight geometries through the host galaxy and include a full accounting of the infrared radiation produced by the absorption and re-radiation of starlight by dust. The optical depth for GeV gamma rays due to direct starlight is less than unity for all host galaxies. At higher energies, > 10 TeV, a spectral cutoff can occur due to the rapidly increasing number of mid- to far-IR intragalactic photons re-radiated by dust. Photons in the extragalactic background light therefore remain the only relevant source of photon–photon opacity for ongoing GRB observations with Fermi-LAT and potential future detections with ground-based gamma-ray telescopes.

Key words: gamma-ray burst: general

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1. INTRODUCTION

Recent observations by the Fermi satellite have confirmed that both long and short gamma-ray bursts (GRBs) are capable of emission at energies > 10 GeV. The rest-frame energies inferred for gamma rays from long-duration GRBs 080916C and 090902B (Abdo et al. 2009a, 2009b) and short GRB 090510 (Omodei et al. 2009) are all in excess of ~60 GeV. These findings raise the question of whether emission might occur at even higher energies, and whether these gamma rays might be observable by Fermi or by ground-based instruments such as MAGIC, VERITAS, and HESS. Electron–positron pair production from interactions between gamma rays and UV–IR photons (Gould & Shen der 1967; Stecker et al. 1992; Madau & Phinney 1996; Gilmore et al. 2009) is an important effect at these energy scales, modifying the spectra of distant extragalactic sources and shrouding the highest energy emission. This effect could thus be a powerful technique for understanding cosmological background radiation (Gilmore et al. 2010; Abdo 2010).

The photon–photon optical depth per unit path length for a gamma ray of energy $E$ is

$$\frac{d\tau(E)}{dl} = \int_{-1}^{1} d(\cos \theta) \frac{(1 - \cos \theta)}{2} \times \int_{E_{\text{min}}}^{\infty} dE' n(E') \sigma(E, E', \theta),$$

(1)

where $n(E')$ is the local density of target photons at energy $E'$ and $\theta$ is the angle of interaction. Here, $\sigma(E, E', \theta)$ is the cross section for interaction (Madau & Phinney 1996), which peaks at twice the minimum energy for pair creation

$$E'_{\text{min}} = \frac{2m_e^2c^4}{E(1 - \cos \theta)}.$$  

(2)

At energies below 1 TeV, it is the optical, UV, and near-IR photons that are responsible for attenuation. Higher energy gamma rays have sufficient energy to produce electron–positron pairs in interactions with longer-wavelength IR photons.

In general, attenuation at a cosmological scale is expected to dominate the pair-production opacity, as the strength of the effect scales with path length through the intervening photon field. Analyses of the interstellar radiation fields within the Milky Way (MW) find significant attenuation of high-energy photons only at several tens of TeV, with negligible absorption at lower energies (Moskalenko et al. 2006). There is strong evidence, however, that long-duration GRBs are associated with deaths of massive stars (Woosley & Bloom 2006), and therefore occur in star-forming regions of galaxies, and that the hosts of these objects often exhibit considerable star formation rates (Bloom et al. 2002; Christensen et al. 2004; Fruchter et al. 2006) and therefore significant numbers densities of UV and optical photons. The prevailing theory for these bursts is that they are associated with some subset of Type Ic supernovae resulting from the deaths of short-lived stars (Woosley 1993; Iwamoto et al. 1998; MacFadyen et al. 2001).

In this paper, we examine the optical depth for gamma rays from a GRB produced by interactions with “local” photons within a host galaxy. Loosely speaking, the opacity from pair production is proportional to the product of the path length and density of target photons at the relevant energy scale. If the line of sight (LOS) to the GRB passes through a region of intense flux from nearby stars, the resulting optical depth could conceivably be equal to or greater than that from intergalactic background photons. Attenuation effects from photon fields on several different length scales could be pertinent. In particular, we will discuss here absorption at sub-parsec scales from the photon field of a binary companion to the GRB progenitor, parsec-scale absorption within the star-forming region of the progenitor site, and finally opacity due to the kiloparsec-scale galactic disk of the host galaxy. In Section 2, we present some simple estimates of the opacity arising on each of these scales. In Section 3, we describe a numerical calculation performed...
to calculate the attenuation for star-forming galactic disks, followed by our conclusions.

2. GAMMA-RAY ATTENUATION AT GALACTIC AND SUB-GALACTIC SCALES

As a simple preliminary approximation, an estimate of $\tau_\gamma$ can be found for a given region by the product

$$\tau_\gamma \approx n_{\text{UV}} R \sigma,$$  \hspace{1cm} (3)

where $R$ is the typical size of the region of interest and therefore the approximate path length of the gamma ray through the photon field, $n_{\text{UV}}$ is the number density of photons near energies corresponding to the peak cross section (maximum in $\sigma (E, E', \theta))$, and $\sigma \approx 0.1 \sigma_T$ is this approximated cross section. Here, $\sigma_T$ is the Thomson cross section.

2.1. Binary Companion

Here, we consider the attenuation of gamma rays by a high-mass binary companion of the GRB progenitor. One class of GRB creation models invokes a companion star at a few stellar radii to form a rapidly spinning helium core (Izzard et al. 2004; Podsiadlowski et al. 2004; Ramirez-Ruiz 2004; Barkov & Komissarov 2010; Yoon et al. 2010), a distance of $10^{10.5}$–$10^{11.5}$ cm for high-mass stars. The effect of radiation from this companion on gamma-ray flux is limited by the radius $R_\gamma$ at which the high-energy flux is emitted from the outflow of the progenitor. Most models place this emission at a distance $\geq 10^{12}$ cm (Piran 2004; Granot et al. 2008; Kumar & Barniol Duran 2009), typically less than unity, for a given separation distance between the progenitor and its companion. We assume here a low-metallicity main-sequence companion star of masses $10^3$ and $10^0$ $\odot$, which are modeled as blackbody sources. From Tout et al. (1996), we assign these two cases luminosities of $10^3$ and $100$ $L_\odot$, respectively. The lower and upper energy of gamma rays of 300 and 100 GeV, respectively. The lower and upper pairs of curves are for a low-metallicity main-sequence companion star of masses $10^3$ $M_\odot$ and $10^0$ $M_\odot$; see the text for details.

2.2. Molecular Cloud

For the case of attenuation by the photon field within a large molecular cloud, we look to surveys of these complexes within the MW and nearby galaxies to estimate the extent and magnitude of a typical photon field. Clouds in the MW typically have sizes $R_{\text{mc}}$ of $10^{5.5}$–$10^{5.5}$ pc and an H$_2$ gas mass as high as $\sim 10^6$–$10^7$ $M_\odot$ (Solomon et al. 1987; Heyer et al. 2001), and other authors confirm similar results for M31 and the Large Magellanic Cloud (LMC; Rosolowsky 2007; Fukui et al. 2008). With the assumption that 5%–10% of this gas forms stars within a time comparable to the lifetime of high-mass stars, 20–30 Myr (Krumholz et al. 2006), we can estimate the highest value likely for our estimate of $\tau_\gamma$ in Equation (3).

For a Salpeter initial mass function (IMF; Salpeter 1955),

$$\frac{dN}{dM} \propto M^{-2.35}; \quad 0.1 M_\odot < M < 100 M_\odot,$$  \hspace{1cm} (5)

we have $\sim 0.005$ high-mass ($\geq 10 M_\odot$) stars per solar mass of gas converted into stars. If we assume that these stars have a typical luminosity of $L_{\ast} = 10^4 L_\odot$, which is mostly emitted in the UV and is responsible for most of this radiation at these wavelengths, then we estimate that the most massive molecular clouds could have $N_c = 5 \times 10^3$ massive stars producing $N_c L_{\ast} = 5 \times 10^7 L_\odot$ in optical–UV photons. The energy density in the cloud can be approximated as

$$\rho_{\text{UV}} = \frac{N_c L_{\ast}}{R_{\text{mc}}^3} \left( \frac{R_{\text{mc}}}{c} \right),$$  \hspace{1cm} (6)

about $6.7 \times 10^{-9}$ erg cm$^{-3}$ under our assumptions. If we assume that this energy exists in the form of UV–optical (i.e., 3 eV) photons, in a cloud of size $R_{\text{mc}} = 10$ pc, then we have a photon number density of $1.4 \times 10^3$ cm$^{-3}$. Applying Equation (3) to

![Figure 1. Minimum gamma-ray production distance $R_\gamma$ from a close binary pair at a given separation for which $\tau_\gamma \leq 1$. The solid and dotted lines are for gamma-ray energies of 300 and 100 GeV, respectively. The lower and upper pairs of curves are for a low-metallicity main-sequence companion star of masses $10^3 M_\odot$ and $10^0 M_\odot$; see the text for details.](image-url)
find the opacity over a path through the cloud, we estimate
\[ \tau_\gamma \sim 3 \times 10^{-3} \]
from UV photons in the most massive stellar birth clouds. We have not accounted for dust extinction in these systems, which can be substantial and would reduce the UV flux and \( \tau_\gamma \).

2.3. Galactic Disk

While it is generally accepted that long-duration GRBs are associated with core-collapse supernovae (Woosley & Bloom 2006; Gehrels et al. 2009), the relation between GRB host galaxies and the population of star-forming galaxies appears to be complex, and recent studies seem to dismiss the idea that GRB rates follow star formation in an unbiased manner (Ramirez-Ruiz et al. 2002; Cen & Fang 2007; Guetta & Piran 2007). Surveys of host galaxies can provide a guide for us to choose general parameters in this project. A survey of GRB host galaxies at a variety of redshifts by Wainwright et al. (2007) found that hosts can typically be described by an exponential profile with a median scale radius of 1.7 kpc; none followed the de Vaucouleurs profile associated locally with elliptical galaxies.

Castro Cerón et al. (2008) analyzed 30 GRB hosts and found typical star formation rates of 0.01–10 \( M_\odot \) yr\(^{-1} \) from an assumed unobscured UV, though the inclusion of dust could raise these values considerably. This paper also mentions that some galaxies in their sample with more poorly constrained spectral energy distributions (SEDs) could have star formation rates as high as a few hundred \( M_\odot \) yr\(^{-1} \). A study of 46 hosts by Savaglio et al. (2009) found star formation rates of 0.01–36 \( M_\odot \) yr\(^{-1} \), with a mean of 2.5, after correcting for dust extinction. Stellar masses in these samples ranged from 10\(^7\) to 10\(^11\) \( M_\odot \) in the former, and from 10\(^8.5\) to 10\(^11.1\) \( M_\odot \) in the latter. However, Perley et al. (2009) have found that even galaxy hosts for obscured “dark” GRBs typically have normal optical colors overall, suggesting that the dust is unevenly distributed or local to the GRB.

In their survey, Castro Cerón et al. (2008) estimate that \( \lesssim 25\% \) of GRB hosts have dust extinction \( A_V \gtrsim 1 \). Savaglio et al. (2009) found an average dust extinction of \( A_V \sim 0.5 \) in a subset of 10 galaxies in their sample; two of these galaxies had \( A_V > 1 \).

Following our method in the last two sections, we can perform an order-of-magnitude estimate of \( \tau_\gamma \) for a rapidly star-forming galaxy. For a given star formation rate, we can estimate the UV flux using the approximation (Madau et al. 1998)

\[ L_{UV} \approx 8 \times 10^{27} \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \text{erg s}^{-1} \text{Hz}^{-1}. \]

For a star formation rate of 100 \( M_\odot \) yr\(^{-1} \) and a galaxy size of 1 kpc, we estimate a total UV output of \( 2 \times 10^{45} \) erg s\(^{-1} \) and consequently a photon energy density similar to that of the molecular cloud in the previous section. From Equation (3), we estimate a gamma-ray opacity
\[ \tau_\gamma \sim 0.3, \]
if this energy is emitted as 3 eV photons.

These findings suggest that the emission from a star-forming galaxy, acting over a path length of a kpc or more, could be a barrier to GeV gamma rays from a GRB within a galaxy. However, this is only an order-of-magnitude estimate of \( \tau_\gamma \), with a high star formation rate and no account of the absorption and re-emission of starlight by dust. Higher star formation rates than we assume here have been seen in GRB-selected submillimeter galaxies (Michałowski et al. 2008), and in extreme cases, galaxies of this type can have rates exceeding 1000 \( M_\odot \) yr\(^{-1} \) (Daddi et al. 2005), albeit with heavy dust obscuration. To better understand the circumstances under which the photon flux from stars and dust in a galaxy might lead to significant attenuation of gamma rays on a kiloparsec scale, we have performed a set of numerical calculations which are described in the next section.

3. NUMERICAL CALCULATIONS OF OPACITY FROM STELLAR DISKS

3.1. Model

In order to accurately estimate the contribution to opacity arising from a compact, rapidly star-forming galaxy, we have performed a simple simulation of a galactic disk and numerically calculated the resulting UV–IR photon field and from this the gamma-ray optical depth along a given LOS. The stellar spectra are calculated using the population synthesis code of Bruzual & Charlot (2003). We assume that the stellar population in our galaxy is formed at a constant rate over a characteristic timescale \( T_\star \). Stars are then distributed in a galactic disk of exponential scale length \( R_e \) and maximum radius \( 3R_e \), with thickness 0.3 \( R_e \). Note that the half-light radius for an exponential profile is 1.68 \( R_e \).

Our calculation includes a simple model for dust absorption and re-emission. Starlight is absorbed using the model of Charlot & Fall (2000), in which starlight is absorbed by two components: an interstellar medium (ISM) component affecting all stars and a molecular cloud component affecting only stars younger than 10\(^7\) yr. We assume the standard ratio for these opacities, in which the ISM is responsible for 30% of the opacity for young populations, and the rest arises from absorption within molecular clouds. The ISM dust component is assumed to have a homogeneous distribution in the same disk as the stellar population. All energy absorbed by dust is re-emitted in the IR. We calculate the emission at wavelengths above 4 \( \mu \)m using the templates of Rieke et al. (2009), which are based on Spitzer observations of local galaxies. We consider face-on dust extinction factors of 0.1, 1.0, and 3.0 in the V-band attenuation \( \tau_V \), broadly corresponding to very low, moderate, and large amounts of reddening. From this normalization, the extinction at other wavelengths is determined by multiplying by a power law in wavelength with index \( -0.7 \). In galaxies with \( \tau_V = 3.0 \), greater than 90% of starlight from stellar populations younger than 500 Myr is absorbed by dust and re-emitted in the IR, so this corresponds to a (U)LIRG-like mode with highly obscured star formation. All of our galaxy spectra are created using a metallicity of [Fe/H] = −1.65. This is somewhat less than the typical metallicity of 1/6 solar that was seen in the sample of Savaglio et al. (2009); we do not expect this to notably impact our final results.

Figure 2 shows the sample spectra for galaxies of two different star formation timescales \( (T_{\text{sf}}) \) and three values for face-on dust extinction \( (\tau_V = 0.1, 1.0, \text{and } 3.0) \), normalized to the same mass. For our calculation, we have considered timescales over the range 10 Myr \( \lesssim T_{\text{sf}} \lesssim 10 \) Gyr. In Figure 3, we show a comparison with the SED for a starbursting GRB host, GRB 000418, as presented in Michałowski et al. (2008). This source is representative of the type of GRB hosts that have the highest inferred star formation rate and are therefore expected to have the largest opacity to gamma rays.
We do not include a luminosity contribution from an active galactic nucleus (AGN) in our calculation. However, our templates for dust re-emission are based on observations of local galaxies, and therefore some degree of AGN contamination in the IR unavoidably exists. Some degree of evolution in the typical IR properties of galaxies likely occurs between local redshifts and those near the peak of the star formation era ($z \sim 2$); Rieke et al. (2009) estimate that these are not larger than a factor of 2. In our model, we assume a scaling law for the galactic disk radius with stellar mass of
\[ R_e \propto M_*^{1/3}, \]
with normalization of 500 pc at $10^9 M_\odot$; this slope is based upon a rough fit to the half-light radius results from a survey of star-forming galaxies in Förster Schreiber et al. (2009), and it is consistent with the more compact galaxies seen in the sample presented in Trujillo et al. (2004). This particular scaling produces galaxies that are more compact than 18 of the 20 GRB hosts with $r_{80} \approx 3 R_e$ in the study of Svensson et al. (2010). Since the disk height is also proportional to $R_e$ in our model, it should be pointed out that for a given set of stellar and dust properties the photon flux density scales as $R_e^{-2}$, and therefore gamma-ray opacity is proportional to $R_e^{-1}$, after accounting for the increase in path length. The UV, optical, and near-IR spectral properties of a unit mass of stars are defined in our model by the assumed dust attenuation factors and star formation timescale, therefore for gamma-ray energies affected solely by these wavelengths ($\ll 500$ GeV) the gamma-ray opacity scales as
\[ \tau_\gamma \propto M_*^{2/3}, \]
when these factors are held fixed.

### 3.2. Results

The primary ingredients of our model are the star formation timescale, dust attenuation factor, and galaxy size and stellar mass which are conjoined in Equation (8), as discussed in the previous section. The other important considerations are the location of the GRB within the disk and the geometry of the LOS path from the GRB to the observer. We fix the location of the GRB at a radius 0.75 $R_e$ (25% of the simulated radius $3 R_e$) and centered within the disk height. Here, we consider two possibilities for the LOS: a “skimming” mode in which the path is toward the galactic center at an angle of incidence of $10^\circ$ to the disk, and a geometry in which the path is face-on relative to the disk, with angle of incidence 90°. The former gives a nearly maximal amount of attenuation for a given galaxy, while the second gives a closer to average amount of absorption.

We have calculated opacities for gamma rays from energies of 1 GeV–100 TeV. In Figure 4, we show the opacity $\tau_\gamma$ for gamma rays at a particular energy for several sets of galaxy properties. Changing from the skimming LOS to one that is perpendicular to the galactic disk is found to reduce $\tau_\gamma$ by a factor of 2–3.
The results in Figure 2 for a galaxy of mass $10^{10} M_\odot$ indicate that attenuation at energies <TeV is significantly less than $\tau_\gamma = 1$ even for the optimal “skimming” geometry and a fast stellar buildup time of 30 Myr. As mentioned in the previous section, the attenuation is expected to be approximately proportional to $M_\odot^{2/3}$, if we assume that galaxy volume scales with mass. The only significant attenuation in these cases is due to the population of mid- and far-IR photons created by thermal and polycyclic aromatic hydrocarbon (PAH) emission, these being much more numerous than the UV, optical, and near-IR photons of direct starlight.

In Figures 5 and 6, we examine the relationship between galaxy mass, star formation timescale (or star formation rate), and the minimum gamma-ray energy for which $\tau_\gamma \geq 1$; these two plots are, respectively, for cases of low and moderate dust extinction ($\tau_V = 0.1$ and 1.0). Results for the largest dust extinction, $\tau_V = 3.0$, are not substantially different from the $\tau_V = 1.0$ case and are not shown. Displaying our results in this way can tell us the approximate energy scale at which photon–photon opacity becomes an important effect on the high-energy spectrum of radiation escaping from the vicinity of the galaxy. In general, the opacity only becomes significant at multi-TeV energies, where gamma rays have sufficient energy of the galaxy. In general, the opacity only becomes significant at multi-TeV energies, where gamma rays have sufficient energy.

4. DISCUSSION

Our results suggest that it is unlikely that the radiation field within a single star-forming region could impact the high-energy (GeV and TeV) gamma-ray emission from a GRB, although our understanding of these regions is limited to nearby galaxies. Significant attenuation due to the emission of a massive binary companion is possible only if the radius of high-energy photon emission is less than predicted by most radiation models.

Large, rapidly star-forming galaxies can form an optically thick barrier only at multi-TeV energies, where attenuation with mid-IR photons can occur, regardless of LOS geometry or dust extinction. However, photons at these energies would already be strongly attenuated by extragalactic background light for all but the closest GRBs ($z \lesssim 0.05$). Creating enough photons in the UV, optical, and near-IR to significantly impact transmission of GeV photons is only possible with star formation rates well in excess of $1000 M_\odot$ yr$^{-1}$, even with a minimal amount of dust attenuation. This requirement could be lowered if galaxies are much more compact than we have assumed, though the galaxy sizes used here are already more compact than most of those in the sample of Trujillo et al. (2004), and these authors mention that the densest objects at high redshift tend to be elliptical galaxies with much lower photon densities.

Clumpy or irregular star formation is one possibility that we have not considered in our numerical calculations, which assume a smooth exponential disk. The total amount of attenuation through the host galaxy is proportional to the photon density over the LOS path. Therefore, the total $\tau_\gamma$ for the galaxy would only be significantly increased from our predictions if a large fraction of the total stars in the galaxy were placed in a much more compact distribution than we have assumed with our exponential profiles. This region would have to contain a much higher density of young stars than the star-forming regions seen in the MW and the LMC, based on the order-of-magnitude analysis of Section 2.2. Merely rearranging star formation into clumpy regions throughout the galaxy would not, in general, affect the total photon field or $\tau_\gamma$, unless those regions were positioned near the LOS path in a stochastic irregularity. In conclusion, both long and short GRB observations can be safely used as powerful tools for understanding the extragalactic background light.

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