Gamma-Ray Bursts and Cosmic Radiation Backgrounds

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Abstract. If gamma-ray bursts trace the cosmic star formation rate to large redshifts, their prompt and delayed emissions provide new tools for early universe cosmology. In addition to probing the intervening matter via absorption lines in the optical band, GRB continua also contribute to the evolving cosmic radiation background. We discuss the contribution of GRBs to the high-energy background, and the effect pair creation off low-energy background photons has on their observable TeV spectra.

INTRODUCTION

Cosmic gamma-ray bursts (GRBs) have redshifts comparable to or perhaps even larger than those of quasars. Indeed, they are the most energetic explosions in the universe, with energies (uncorrected for beaming) of order $M_\odot c^2$. Their host galaxies are often sub-$L_\star$, but actively forming stars at rates typical for galaxies in the early universe. The current paradigm associates GRBs with the formation of black holes in massive, rapidly rotating stars, or with the merger of compact star binaries. GRBs thus trace directly, or perhaps with a short delay, the cosmic star formation history, and may be the most easily detectable signposts of the first generation of stars (e.g., [1] and references therein). The redshifted gamma-ray flux from GRBs contributes to the evolving radiation background of the universe, as discussed in the next section, and at the same time serves as a probe of the cosmic radiation field through electron-positron pair creation absorption of their highest energy photons [2][3].

The cosmic microwave background (CMB) provides abundant soft photons for pair production of very high energy photons (in the TeV - PeV regime), but at lower energies (GeV-TeV regime) the target photons are optical and IR photons produced by stars and reprocessed by surrounding dust. Cosmic chemical evolution is intimately linked to the cosmic star formation history, and the present day extragalactic background light (EBL) provides a record of that history. Gamma-ray sources, such as GRBs and blazars, probe the evolution of this photon field through absorption effects at high energies (e.g., [2][3]). There are only three nearby active galaxies for which this absorption effect has been observed, Mrk 421, Mrk 501 (both at $z = 0.03$), and BL Lac (at $z = 0.044$). TeV emission from GRBs has only been reported for GRB970417a [4]. GRB power spectra ($\nu f_\nu$) typically peak at photon energies of a few hundred keV, but their power-law high energy emission may extend well into the GeV or even TeV regime. EGRET aboard the Compton Observatory has established that emission above 100 MeV is common, and in the case of GRB940217 a maximum photon energy of $E \sim 20$ GeV was determined [5].

Theoretical models (e.g., [6]) certainly suggest that GeV-TeV emission should be expected for a significant fraction of all bursts. The next generation GLAST experiment is expected to observe a large number of GRBs with spectral coverage up to 300 GeV. Ongoing improvements of ground-based experiments (VERITAS, HESS, HEGRA, MILAGRO, MAGIC, ...) lead to reduced sensitivities and thresholds, thus overlapping with space-based experiments. It will thus be possible to explore GRB spectra from the X-ray regime to the TeV regime, and the effects of propagation effects such as the above mentioned electron-positron pair creation must be taken into account.

To correct for $\gamma \gamma$ absorption, it is necessary to determine the cosmic evolution of the target photon distribution function, which we refer to as the metagalactic radiation field (MRF). In the third section of this paper we briefly describe our simulations of the evolving low-energy MRF, and demonstrate the extinction effect in the high energy part of GRB spectra. The gamma-ray horizon of the universe can perhaps be probed with GRBs, which would provide another powerful tool for the study of stellar evolution on the cosmic scale. GRB detections point to the onset of star formation in the universe, and their high energy spectra probe the production of light throughout the cosmic ages.
FIGURE 1. The observed gamma-ray background and estimated contributions from supernovae, radio galaxies, and gamma-ray bursts [7]–[9].

THE GAMMA-RAY BACKGROUND

The unresolved cosmic gamma-ray background (CGB) from 10 KeV to 100 GeV is predominantly due to the superposition of three source populations (e.g., [7] and references therein): Seyfert galaxies, which dominate below $\sim 100$ keV; blazars, which dominate above a few MeV, and Type Ia supernovae, which fill the gap between the contributing active galaxies. The flux in the MeV regime, detected with COMPTEL and SMM, can be accounted for with nuclear line emission from the decay chain $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, escaping from expanding supernova ejecta (e.g. [8]). Despite their lower rate SNIa contribute the bulk of the CGB in the MeV regime due to their higher yields, and low mass envelopes. Core collapse supernovae (SNII) do contribute about 1% of the flux, as do radio galaxies such as Cen A ([9]). Figure 1 shows the observations and the contributions from various sources. The fact that SNIa so closely match the observed spectrum of the CGB places significant constraints on the cosmic star formation rate SFR(z). Most of observed flux is due to the integrated emission from supernovae that exploded at redshifts less than $\sim 1$, but a SFR that continues to rise as rapidly as observed between the present epoch and $z \sim 1$ would overproduce the CGB. The MeV data thus provide an independent constraint on the high-z star formation history of the universe.

Throughout the observable universe GRBs occur at significantly lower rates than supernovae, but their high $\gamma$-ray luminosity suggests a possible contribution to the CGB. Watanabe and Hartmann [9] used the BATSE data from the 4B catalog to estimate the contribution of observed GRBs (corrected for Earth blocking) to the CGB. As Figure 1 shows, GRBs compete with radio galaxies and SNII, but do not contribute a large portion of the observed background. Still, their role could be significant by reducing some of the deficit at 200-400 keV between the observed spectrum and the predicted flux from Seyfert galaxies.

THE LOW-ENERGY BACKGROUND

Numerical simulations of hierarchical structure formation in a globally homogeneous Universe are tractable, but connecting the evolving gravitational structures to observable fluxes of electromagnetic radiation involves uncertain empirical descriptions of star formation, supernova feedback, and the dust-gas-star interplay. The necessary input comes from extensive observational campaigns, such as deep galaxy surveys, which measure the number of galaxies, morphological types, colors, fluxes, and distances in presumably representative solid angles out to large redshifts. The wealth of information derived from these observations can significantly complicate efforts to link theories of galaxy evolution and large scale structure formation. It is helpful to single out key quantities for which predictions can be compared with observations. One such quantity is the cosmic star formation rate (SFR) and its associated metagalactic radiation field (MRF). The MRF at $z = 0$ is commonly referred to as Extragalactic Background Light (EBL). The contribution of galaxies to the MRF is most significant between the far-infrared and the ultraviolet, while at longer wavelengths the 2.7 K microwave background (CMB) radiation from the big bang dominates.

In principle, the evolution of the MRF should be predictable from structure formation models [10] so that the observed MRF could be used to infer the role of AGNs, low surface brightness objects, and the decays of relic particles, or to single out global cosmological parameters. However, these models still rely on many uncertain parameters, and we are far from the ultimate goal of a first principles theory of the MRF. Here we compute the MRF directly from the global SFR inferred from tracers of cosmic chemical evolution, such as various Lyman $\alpha$ absorber systems, or from deep galaxy surveys. The spectral energy distribution (SED) for the globally averaged stellar population residing in galaxies can be estimated with population synthesis models [11] available for various input parameters, of which the initial mass function (IMF) and metallicity ($Z$) are the most important ones. Reprocessing by gas and dust is taken into account explicitly via some model of the evolution of the dust and gas content in galaxies, in combination with assumed dust properties derived from local observations in the Milky Way. The details of our modeling of the MRF are presented in [12].
Observational attempts to determine or constrain the present-day background face severe problems due to emissions from the Galaxy, which can introduce large systematic errors [13]. Nevertheless, studies with COBE have resulted in highly significant detections of a residual diffuse IR background, providing an upper bound on the MRF in the IR regime. Similarly, the cumulative flux from galaxies detected in deep HST or ISO exposures provide useful lower limits to the present-day MRF (e.g., [13]).

The method for calculating the MRF from a given SFR relies on an accurate knowledge of evolving stellar spectra and the reprocessing of star light in various dusty environments. Luminosity evolution of stellar populations is sensitive to the IMF, evolution of the mean cosmic metallicity, and the amount of interstellar extinction. Starting point of any model is the spectral energy density (SED) produced by a population of stars resulting from an instantaneous burst of star formation (commonly normalized to the mass of stars formed). Because star formation is an ongoing process with relatively short time scales of $10^5$-$7$ yrs, the starburst spectra can be directly convolved with the global SFR, $\dot{\rho}_s(z)$, to derive the evolution of the global luminosity density due to cosmic star formation. The SEDs are constructed from realistic stellar evolution tracks combined with detailed atmospheric models (e.g., [11]). The temporal evolution of the specific luminosity, $L_\nu(t)$ (in erg s$^{-1}$Hz$^{-1}$ per unit mass of stars formed) is then determined by the choices of IMF and the initial stellar metallicity.

From the population synthesis starburst models we obtain the comoving emissivity (luminosity density) at cosmic epoch $t$ from the convolution

$$\mathcal{E}_\nu(t) = \int_{z_m}^{z} L_\nu(t-t')\dot{\rho}_s(t')dt' \text{ (ergs}^{-1}\text{Hz}^{-1}\text{Mpc}^{-1})$$

where $\dot{\rho}_s(t) = \rho_s(z)$ is the star formation rate per comoving unit volume. Rewriting Eq. (1) in terms of redshift, $z = z(t)$, yields

$$\mathcal{E}_\nu(z) = \int_{z}^{z_m} L_\nu(t(z)-t(z'))\dot{\rho}_s(z') \left[\frac{dt'}{dz'}\right] dz'$$

where we assumed that star formation began at some finite epoch $z_m = z(t_m)$. For given evolution of the emissivity a second integration over redshift yields the energy density, or, after multiplication with $c/4\pi$, the comoving power spectrum of the MRF

$$P_\nu(z) = \nu \mathcal{E}_\nu(z) = \nu \frac{c}{4\pi} \int_{z}^{z_m} \mathcal{E}_\nu(z') \left[\frac{dt'}{dz'}\right] dz' ,$$

with $\nu' = \nu(1+z')/(1+z)$. Cosmological parameters enter through $dt/dz$, given by

$$\frac{dt}{dz} = \frac{1}{H_0(1+z)E(z)}$$

with an equation of state

$$E(z)^2 = \Omega_\nu(1+z)^4 + \Omega_m(1+z)^3 + \Omega_R(1+z)^2 + \Omega_\Lambda .$$

The term proportional to $\Omega_\nu$ takes into account the contribution from relativistic components such as the CMB and star light, although the latter would also require a new function describing the production of light as a function of time. The density parameter of this component is defined as $\Omega_\nu = H_0^2/\rho_{crit} c^2$, where $H_0$ refers to the relativistic energy density and $\rho_{crit}$ is the critical density of the universe; $\rho_{crit} = 3H_0^2/8\pi G = 10.54 h^2$ keV/cm$^3$.

The average metallicity of gas in galaxies slowly increases with cosmic time, but the present-day value is not known precisely (e.g., [14]). We thus adopt an average extinction curve

$$A_\lambda = 0.68 \cdot E(B-V) \cdot R \cdot (\lambda^{-1} - 0.35)$$

with $R = 3.2$ and where $A_\lambda$ with $\lambda$ [\mu m] determines the absorption coefficient according to $g(\lambda) = 10^{-0.4A_\lambda}$. Reemission by dust is calculated as the sum of three modified Planck spectra

$$L_\nu^d(L_{bol}) = \sum_{i=1}^{3} c_i(L_{bol}) \cdot Q\lambda \cdot B\lambda(T_i)$$

where $Q\lambda \propto \lambda^{-1}$. Two temperatures characterize warm and cold dust in galaxies, and one temperature is included to emulate a PAH component, which is also assumed to emit like a Blackbody. Dust in the ISM of the Milky Way is known to coexist at several different temperatures, determined by the distances from various heat sources. Hot dust has temperatures ranging from 50 K to 150 K-200 K when the dust is in equilibrated within HII regions, or near massive stars or compact accreting sources. Radiation from this dust component predominantly emerges in the mid-infrared and reprocesses only a small fraction of the stellar luminosity. Warm dust with temperatures between 25 K and 50 K corresponds to regions heated by the mean interstellar radiation field. Dust inside molecular clouds is shielded against high-energy radiation, and thus appears at low temperatures between 10 K and 25 K. Very cold dust at temperatures of 10 K or less can be present in the densest parts of molecular clouds or in outer regions of the galaxy where the flux of the interstellar radiation field has dropped to the value of the MRF.

The cosmic star formation rate density SFR($z$) has been determined with different methods and for large set of input data. Many of these studies suggest that the original Madau curve [15] should be considered a lower limit, and that realistic rates could be larger by a factor 2–3 at all redshifts. A review of published SFR($z$) functions shows that we do not yet understand systematic effects well enough to obtain a reliable estimate for
SFR(z). This is especially true at redshifts beyond unity. This uncertainty enters in the final step of computing the MRF, the integration of the emissivity over cosmic time using Eq. (3). The evolution of the resulting MRF spectrum is shown in Fig. 2 for several redshifts.

**ABSORBED TEV SPECTRA**

Gamma-ray absorption due to $\gamma\gamma$-pair creation on cosmological scales depends on the line-of-sight integral of the evolving density of low-energy photons in the Universe, i.e. on the history of the diffuse, isotropic radiation field. Above we briefly discussed our semi-empirical MRF model, which is based on stellar light produced and reprocessed in evolving galaxies and calibrated with the EBL. The optical depth of the universe is given by

$$\tau_{\gamma\gamma}(E, z) = \int_0^z d\bar{z}(\bar{\sigma}, z) \langle \sigma(E, z) \rangle$$  \hspace{1cm} (8)

where E is the energy of the observed photon, $n(\varepsilon, z)$ represents the evolving MRF, and the angle averaged cross section $\langle \sigma \rangle$ is of order of the Thomson cross section, $\sigma_T$.

Using a power law spectrum as template (with an intrinsic cut-off above E $\sim$ 1 TeV) we show in Figure 3 how the line of sight optical depth to $\gamma\gamma$-pair creation affects the spectra. It is apparent that most GRB spectra, if they intrinsically extend into the TeV regime, are severely affected as soon as their redshifts exceed $z \sim$ 0.1. If the GRB distribution traces the cosmic star formation history, we expect only a a small fraction of all bursts to be close enough for detectable TeV emission. Ongoing efforts to observe TeV emission from GRBs have so far only turned up one possible detection (GRB 970417a), which suggests either that GRBs do not commonly radiate in this regime, or that they do but are extinct by the opacity along the line of sight. If the latter interpretation is correct, TeV detections of GRBs (for example with ground based muon detectors; [16]) will be rare [2] but valuable probes of GRB physics and MRF evolution. TeV GRBs could significantly enhance the insights gathered from the limited set of TeV blazars (e.g., [17])

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