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THE POLARIZATION DEPENDENCE OF $\gamma\gamma$ ABSORPTION—IMPLICATIONS FOR γ-RAY BURSTS AND BLAZARS

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ABSTRACT

This paper presents an analysis of the dependence of the opacity for high-energy γ-rays to $\gamma\gamma$ absorption by low-energy photons on the polarization of the γ-ray and target photons. This process has so far only been considered using the polarization-averaged $\gamma\gamma$ absorption cross section. It is demonstrated that in the case of polarized γ-ray emission, subject to source-intrinsic $\gamma\gamma$ absorption by polarized target photons, this may lead to a slight overestimation of the $\gamma\gamma$ opacity by up to $\sim$10% in the case of a perfectly ordered magnetic field. Thus, for realistic astrophysical scenarios with partially ordered magnetic fields, the use of the polarization-averaged $\gamma\gamma$ cross section is justified for practical purposes, such as estimates of minimum Doppler factors inferred for γ-ray bursts and blazars, based on $\gamma\gamma$ transparency arguments; this paper quantifies the small error incurred by the unpolarized-radiation approximation. Furthermore, it is shown that polarization-dependent $\gamma\gamma$ absorption of initially polarized γ-rays can lead to a slight increase in the polarization beyond the spectral break caused by $\gamma\gamma$ absorption. This amount is distinctly different from the change in polarization expected if the same spectral break were produced by a break in the underlying electron distribution. This may serve as a diagnostic of whether $\gamma\gamma$ absorption is relevant in sources such as γ-ray bursts and blazars where the γ-ray emission may be intrinsically highly polarized.

Key words: galaxies: jets – gamma-ray burst: general – gamma rays: galaxies – radiation mechanisms: non-thermal – relativistic processes

Online-only material: color figures

1. INTRODUCTION

It has long been recognized (e.g., Gould & Schréder 1967) that high-energy γ-rays from astronomical sources are subject to $\gamma\gamma$ absorption by low-energy target photons if the energy threshold for pair production $\epsilon_\gamma \, \epsilon_t \, (1 - \mu) \geqslant 2$ is fulfilled. Here ϵ_γ and ϵ_t are the energies of the γ-ray and the soft target photon, respectively, normalized to the electron rest-mass energy, $\epsilon = E/(m_e c^2)$, and $\mu = \cos\theta$ is the cosine of the collision angle. This process is expected to limit the very-high-energy (VHE) γ-ray horizon out to which VHE γ-rays may be detectable by ground-based γ-ray observatories due to $\gamma\gamma$ absorption in the extragalactic background light (EBL; e.g., Stecker et al. 1992; Finke et al. 2010, and references therein). The apparent absence of $\gamma\gamma$ absorption signatures also provides evidence for relativistic beaming in γ-ray bursts (GRBs; e.g., Baring 1993) and blazars (e.g., Dondi & Ghisellini 1995).

When considering the effects of $\gamma\gamma$ absorption, to the author's knowledge, all previous works have used the polarization-averaged cross section for $\gamma\gamma$ absorption (or simplified approximations derived from it),

$$\sigma_{\gamma\gamma}^{\rm ave} = \frac{3}{16} \, \sigma_T \, (1 - \beta^2) \times \left\{ (3 - \beta^4) \, \ln\left(\frac{1+\beta}{1-\beta}\right) - 2\,\beta\,(2 - \beta^2) \right\} \quad (1)$$

(Jauch & Rohrlich 1976), where

$$\beta = \sqrt{1 - \frac{2}{\epsilon_\gamma \, \epsilon_t \, (1 - \mu)}} \quad (2)$$

is the normalized (to the speed of light) velocity of the electron and positron produced in the center-of-momentum frame of the collision. In the case of $\gamma\gamma$ absorption of cosmological γ-rays by the EBL, the use of the polarization-averaged cross section is reasonable as the EBL is expected to be, on average, unpolarized on cosmological scales.

However, this may not be the case when considering source-intrinsic $\gamma\gamma$ absorption in GRBs and blazars. In GRBs, the X-ray through γ-ray emission is commonly interpreted as synchrotron radiation by shock-accelerated electrons, possibly with an admixture of thermal radiation from a photosphere of the initial fireball. In an ordered magnetic field, synchrotron radiation is expected to be polarized, and Compton scattering in the photosphere of structured GRB outflows may also result in non-zero polarization of a possible photospheric emission component (Lundman et al. 2014). In blazars, the low-energy emission, potentially acting as targets for intrinsic $\gamma\gamma$ absorption, is generally agreed to be produced by synchrotron radiation of relativistic electrons (see, e.g., Böttcher 2007 for a review of blazar emission models). In the case of synchrotron self-Compton (SSC) radiation or hadronic emission scenarios for the γ-ray emission, the γ-rays are also expected to be polarized (Zhang & Böttcher 2013). Therefore, when considering the intrinsic $\gamma\gamma$ opacity of high-energy γ-ray sources, the effects of polarization may not be negligible.

The study of potential effects of the polarization dependence of the $\gamma\gamma$ opacity in GRBs and blazars is the aim of this paper. Section 2 contains a brief discussion of the polarization-dependent cross section for $\gamma\gamma$ absorption. Section 3 presents a simple model scenario to illustrate the potential impact of the polarization dependence of the $\gamma\gamma$ absorption cross section in the case of intrinsic absorption of polarized γ-rays by a target photon field with the same polarization geometry as the γ-rays; this is generally expected when γ-rays and target photons are produced co-spatially. Section 4 contains a discussion of the results.

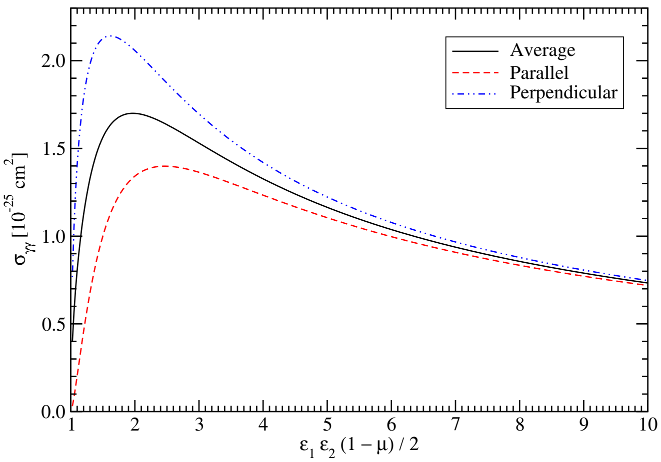

Figure 1. Polarization-dependent $\gamma\gamma$ absorption cross section as a function of center-of-momentum electron energy squared, $\gamma_{\rm cm}^2 = \epsilon_\gamma\,\epsilon_t\,(1-\mu)/2$, for the case of parallel and perpendicular polarization directions of the γ-ray and target photons, respectively.

(A color version of this figure is available in the online journal.)

2. THE POLARIZATION-DEPENDENT $\gamma\gamma$ ABSORPTION CROSS SECTION

The polarization-dependent cross section for $\gamma\gamma$ absorption has been calculated by Breit & Wheeler (1934). Using the same nomenclature as employed in (Jauch & Rohrlich 1976; e.g., Equations (1) and (2)), the cross section $\sigma_{\gamma\gamma}^{\parallel}$ for the case of parallel linear-polarization vectors of the γ-ray and target photon is given by

$$\sigma_{\gamma\gamma}^{\parallel} = \frac{3}{16}\,\sigma_T\,(1-\beta^2) \times \left\{ \frac{5+2\,\beta^2-3\,\beta^4}{2}\,\ln\left(\frac{1+\beta}{1-\beta}\right) - \beta\,(5-3\,\beta^2)\right\}, \tag{3}$$

and $\sigma_{\gamma\gamma}^{\perp}$ for the case of perpendicular polarization vectors:

$$\sigma_{\gamma\gamma}^{\perp} = \frac{3}{16}\,\sigma_T\,(1-\beta^2) \times \left\{ \frac{7-2\,\beta^2-\beta^4}{2}\,\ln\left(\frac{1+\beta}{1-\beta}\right) - \beta\,(3-\beta^2)\right\}. \tag{4}$$

One can easily verify that $(\sigma_{\gamma\gamma}^{\parallel} + \sigma_{\gamma\gamma}^{\perp})/2 = \sigma_{\gamma\gamma}^{\rm ave}$ according to Equation (1). These cross sections as a function of center-of-momentum energy are plotted in Figure 1. It can be seen that the cross section for the case of perpendicular polarization directions (1) peaks at lower energies than the average and the parallel cases and (2) peaks at a value about 1.5 times higher the peak cross section for the parallel case.

This means that the $\gamma\gamma$ absorption of polarized γ-ray photons by target photons with identical polarization direction is suppressed compared to the unpolarized case (and compared to the case of absorption on target photons with polarization direction perpendicular to that of the γ-ray photon). This may be important in cases where polarized γ-rays are produced co-spatially with synchrotron target photons, with preferred electric-field vector orientations perpendicular to a globally ordered magnetic field in the emission region. If the γ-rays are co-spatially produced, e.g., by SSC scattering, proton synchrotron radiation, or synchrotron emission of secondary particles in photo-pion-induced cascade processes, then they are expected to have the same polarization direction as the target electron–synchrotron photons (Zhang & Böttcher 2013). In this case, we expect two consequences of the polarization-dependence of the cross sections (Sections 3 and 4). (1) The overall $\gamma\gamma$ opacity is reduced compared to $\gamma\gamma$ absorption by unpolarized photons. (2) The degree of polarization Π is expected to increase in a partially self-absorbed regime (see, e.g., Panaitescu et al. 2014 for a discussion of possible signatures of partially self-absorbed SSC emission in GRBs), because the dominant polarization direction of the γ-ray beam will be less affected by $\gamma\gamma$ absorption since it is primarily interacting with the sub-dominant polarization direction of the target photon field and vice versa. These effects will be illustrated and studied more quantitatively with a simple toy model of a synchrotron-dominated γ-ray source in the next section.

3. EFFECTS ON A SYNCHROTRON-DOMINATED γ-RAY SOURCE

In this section, we investigate the potential effects of polarization-dependent $\gamma\gamma$ absorption in an idealized case of a synchrotron-dominated γ-ray source, as commonly assumed for the non-thermal emission from GRBs. The model assumes a spherical emission region containing a perfectly ordered magnetic field and considers a non-thermal electron synchrotron spectrum characterized by an energy index α, i.e., an emission coefficient $j_\nu \propto \nu^{-\alpha}$, extending from $\epsilon_1 = 10^{-6}$ without cut-off into the γ-ray regime. Additional polarized high-energy and VHE γ-ray photons may be produced, e.g., by proton-synchrotron radiation or synchrotron emission of secondary leptons produced in photo-pion pair cascades (e.g., Zhang & Böttcher 2013). The synchrotron emissivity is normalized to a total synchrotron compactness $\ell = \sigma_T\,L_{\rm sy}/(4\pi\,R\,\langle\epsilon\rangle m_e c^3) \sim 1$, so that $\gamma\gamma$ absorption effects are expected to become important at high energies. Based on the spectral index α, the synchrotron spectrum is characterized by a degree of polarization,

$$\Pi \equiv \frac{j_\perp - j_\parallel}{j_\perp + j_\parallel} = \frac{\alpha+1}{\alpha+5/3}, \tag{5}$$

from which we find the emission coefficients with electric-field vector orientations perpendicular and parallel to the magnetic field, $j_\perp = j\,(1+\Pi)/2$ and $j_\parallel = j\,(1-\Pi)/2$, respectively. For the case study in this section, let us consider the $\gamma\gamma$ opacity of a synchrotron γ-ray beam emitted perpendicular to the B field. Due to the dependence of the synchrotron emissivity on the pitch angle χ of relativistic particles, $j_\nu(\chi) \propto \sin^2\chi$, the majority of polarized synchrotron photons is expected to be emitted in this direction ($\chi = \pi/2$). Let us further choose the direction of propagation of the γ-ray to be the z-axis, and the B field to be along the y-axis. We define θ as the angle that a target photon's momentum makes with the z-axis (and, thus, the γ-ray photon momentum), and ϕ as the azimuthal angle around the z-axis, with $\phi = 0$ in the (y, z) plane. The γ-ray photon then has polarization vectors given by $\hat{s}_{\gamma,\perp} = \hat{x}$ and $\hat{s}_{\gamma,\parallel} = \hat{y}$. One then finds that the polarization vector $s_{t,\parallel}$ parallel to the magnetic field projection onto the plane perpendicular to the direction of propagation of any target photon interacting with the γ-ray from an angle (θ, ϕ) forms an angle ψ with $s_{\gamma,\parallel}$ given by $\cos\psi = \hat{s}_{\gamma,\parallel}\cdot\hat{s}_{t,\parallel} = \sqrt{1-\sin^2\theta\,\cos^2\phi}$. Using this result, one can find the $\gamma\gamma$ absorption coefficients for γ-rays, with electric-field vectors parallel and perpendicular to the

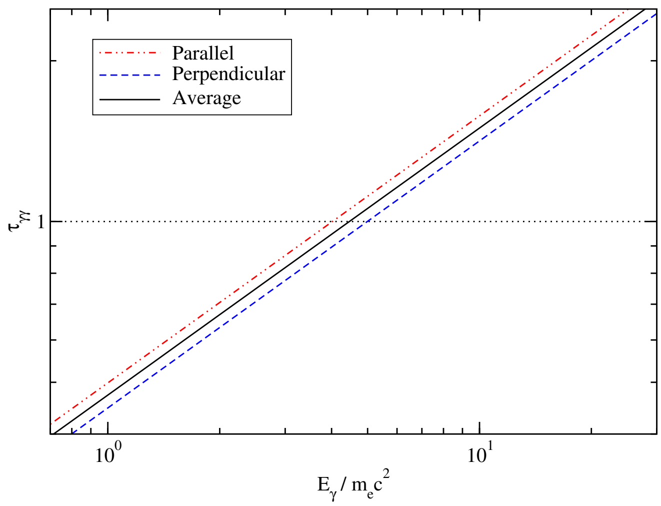

Figure 2. Polarization-dependent $\gamma\gamma$ opacity as a function of γ-ray photon energy, in a synchrotron-dominated source, for photons propagating perpendicular to the magnetic field, in a source with compactness $\ell = 1$, with synchrotron spectral index $\alpha = 0.5$. The figure illustrates that the opacity for γ-rays with electric-field vectors perpendicular to the B field (i.e., the dominant polarization direction) is about 10% smaller than for photons with E field vectors parallel to B.

(A color version of this figure is available in the online journal.)

magnetic field, as

$$\kappa_\nu^\perp = \int_0^\infty d\epsilon \int_{4\pi} d\Omega\,(1-\mu) \cdot \left\{\sigma_{\gamma\gamma}^\parallel (n^\perp[\epsilon,\Omega]\,\cos^2\psi + n^\parallel[\epsilon,\Omega]\,\sin^2\psi) + \sigma_{\gamma\gamma}^\perp (n^\parallel[\epsilon,\Omega]\,\cos^2\psi + n^\perp[\epsilon,\Omega]\,\sin^2\psi)\right\} \tag{6}$$

and

$$\kappa_\nu^\parallel = \int_0^\infty d\epsilon \int_{4\pi} d\Omega\,(1-\mu) \cdot \left\{\sigma_{\gamma\gamma}^\parallel (n^\parallel[\epsilon,\Omega]\,\cos^2\psi + n^\perp[\epsilon,\Omega]\,\sin^2\psi) + \sigma_{\gamma\gamma}^\perp (n^\perp[\epsilon,\Omega]\,\cos^2\psi + n^\parallel[\epsilon,\Omega]\,\sin^2\psi)\right\}, \tag{7}$$

where the photon densities $n^\perp$ and $n^\parallel$ are evaluated based on the emissivities $j_\parallel$ and $j_\perp$ as outlined above.

Figure 2 shows the resulting $\gamma\gamma$ opacities for a source with compactness $\ell = 1$ and a synchrotron spectral index of $\alpha = 0.5$. Both the polarization-dependent and the polarization-averaged opacities show the well-known energy dependence $\tau_{\gamma\gamma} \propto \epsilon^\alpha$. As expected, the $\gamma\gamma$ opacity for photons with parallel polarization direction is larger than that for photons with perpendicular (the dominant) polarization direction. However, the effect is smaller than the difference in the peak values of the respective cross sections, since the target photon field is not 100% polarized, thus mitigating the effect. Still, the difference between the opacities in the two polarization directions is about 10% in this case.

Given an expected optically thin synchrotron flux $F_\nu^{\rm int}$ emerging from the spherical synchrotron source considered here, the emerging spectrum $F_\nu^{\rm obs}$ including the effects of $\gamma\gamma$ absorption is calculated separately for both polarization directions as

$$F_\nu^{\rm obs} = F_\nu^{\rm int}\,\frac{1 - e^{-\tau_{\gamma\gamma}}}{\tau_{\gamma\gamma}}. \tag{8}$$

The degree of polarization Π of the emerging spectrum is then evaluated based on the emerging fluxes with parallel and perpendicular polarization directions, i.e., $\Pi = (F_\perp - F_\parallel)/(F_\perp + F_\parallel)$. The result for our baseline example is plotted in Figure 3. One sees the expected spectral break $\Delta\alpha_\gamma = \alpha_{\rm target} = \alpha = 0.5$ in accordance with Equation (8). The top panel illustrates the effect mentioned in the previous section, that the dominant (perpendicular) polarization direction is less affected by $\gamma\gamma$ absorption than the sub-dominant (parallel) one, leading to an increase of the degree of polarization Π toward the optically thick regime.

While the change of the degree of polarization, $\Delta\Pi$, expected from polarization-dependent $\gamma\gamma$ absorption is a rather small effect ($\Delta\Pi = 2.7\%$), it can be compared to the change expected if the associated spectral break is due to a break in the underlying electron distribution. In that case, one expects a change $\Delta\Pi = \Delta([\alpha+1]/[\alpha+5/3])$. For a break from $\alpha = 0.5 \rightarrow 1$, this would yield a change of $\Delta\Pi = 5.8\%$.

Figure 4 illustrates how these results depend on the spectral index α of the synchrotron spectrum. The upper panel shows

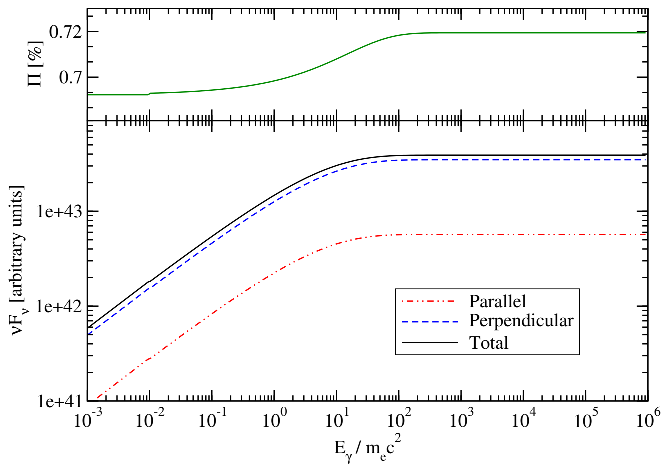

Figure 3. Polarization-dependent flux spectrum (lower panel) and degree of polarization as a function of photon energy (upper panel). Parameters are the same as for Figure 2.

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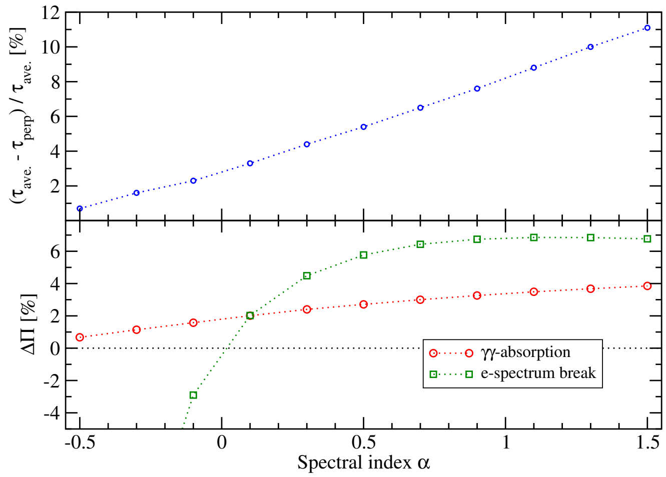

Figure 4. Upper panel: ratio of unpolarized (i.e., average) to polarized (perpendicular) $\gamma\gamma$ opacity as a function of spectral index α. Lower panel: change of the degree of polarization Π across the spectral break, as a function of spectral index α, expected for a break caused by polarization-dependent $\gamma\gamma$ absorption (circles) and for a break caused by a break in the underlying electron spectrum (squares).

(A color version of this figure is available in the online journal.)

that the use of the average (unpolarized) $\gamma\gamma$ opacity may overestimate the actual opacity for polarized γ-rays by up to $\sim$10% for a relatively steep intrinsic spectrum. The lower panel compares the change in γ-ray polarization Π across the spectral break between the two cases—one caused by $\gamma\gamma$ absorption and the other by a break in the underlying electron distribution. While the polarization change due to $\gamma\gamma$ absorption is always expected to be at the $\lesssim$4% level, a break in the underlying electron distribution may cause much larger changes. Below we will discuss whether this may be used as a diagnostic of the importance of $\gamma\gamma$ absorption in the formation of the high-energy spectra of GRBs and blazars.

4. SUMMARY AND DISCUSSION

The main results of the study presented in the previous sections can be summarized as follows.

1. The use of unpolarized (average) $\gamma\gamma$ opacity may overestimate the actual $\gamma\gamma$ opacity by a small amount, up to $\sim$10% in cases where high-energy γ-rays and target photons have identical preferred polarization directions, and the magnetic field is perfectly ordered. This effect becomes larger with the increasing spectral index of the target photon field.
2. Polarization-dependent $\gamma\gamma$ absorption leads to a spectral break in the emerging γ-ray spectrum, which is accompanied by a small increase of the percentage polarization Π, which is, for spectral indices $\alpha \gtrsim 0.2$, smaller than the expected change in polarization, resulting from a break in the underlying electron distribution.

Both in the case of GRBs and blazars, the target photon field for $\gamma\gamma$ absorption is most likely of synchrotron origin, and therefore expected to be polarized. The non-thermal γ-ray emission from GRBs is also commonly attributed to synchrotron emission (and possibly SSC radiation), while that of blazars may be due to SSC emission or proton-induced processes, such as proton-synchrotron or synchrotron radiation from photo-pion-induced secondaries. In those cases, the γ-ray emission from blazars is also expected to be polarized. The study presented here has shown that the use of the unpolarized $\gamma\gamma$ opacity may slightly overestimate, e.g., the minimum Lorentz factors of blazars and GRBs.

In our simple toy model, a perfectly ordered magnetic field has been assumed. From the observed optical polarization, e.g., of blazars, reaching maximum values of $\Pi \lesssim 40\%$, one can infer that due to a partial disorder in the B field, the degree of polarization of the γ-ray and target photon fields is reduced to at most about 50% of the level expected for a perfectly ordered B field. Therefore, realistically, one may expect that $\gamma\gamma$ opacities may be overestimated by no more than $\sim$5%, which—for most practical purposes—is a sufficiently small error to justify the use of the polarization-averaged $\gamma\gamma$ cross section.

An additional, simplifying assumption made in our toy model was the extension of the polarized target photon field into the γ-ray regime without any cut-off. A high-energy cut-off of the synchrotron target photon spectrum would result in an increased degree of polarization at and beyond the (normalized) cut-off energy $\epsilon_{\rm cut}$. This will result in a larger effect of the polarization dependence of the $\gamma\gamma$ absorption cross section at γ-ray photon energies $\epsilon_\gamma \lesssim 1/\epsilon_{\rm cut}$, where the overestimation of the $\gamma\gamma$ opacity when using the polarization-averaged cross section would become more severe than discussed above.

The measurement of high-energy polarization is a very challenging task. However, satellite-borne instruments, such as SPectrometer on *IMAGER* and Imager on Board the *INTEGRAL* Satellite, have already been used successfully to constrain the hard X-ray/soft γ-ray polarization from GRBs (Dean et al. 2008; Forot et al. 2008). Design studies for the upcoming *ASTRO-H* mission suggest that it may also be able to detect polarization in the 50–200 keV energy band (Tajima et al. 2010). It has also been suggested that the Large Area Telescope (LAT) on board the *Fermi* Gamma-Ray Space Telescope may be able to detect γ-ray polarization in the energy range $\sim$30–200 MeV when considering pair-conversion events occurring in the silicon layers of the detector by taking advantage of the polarization-dependent direction of motion of the electron–positron pairs produced in the γ-ray pair-conversion process (Bühler et al. 2010). For bright γ-ray sources, degrees of polarization down to $\sim$10% may be detectable. However, the feasibility of such γ-ray polarization measurements with *Fermi*-LAT is highly controversial. The proposed PANGU and GAMMA-LIGHT mission (Wu et al. 2014; Morselli et al. 2014), due to the absence of any tungsten conversion layers in its design, may provide substantial progress in the ability to measure γ-ray polarization. With such advances, it may be feasible to detect the γ-ray polarization of GRBs and blazars. This will open up the avenue to (1) more precisely determine the expected $\gamma\gamma$ opacity constraints relevant to these sources and (2) identify the nature of spectral breaks in the γ-ray spectra of GRBs and blazars, which will afford deeper insight into the nature of the underlying electron distribution and, hence, the mechanisms leading to the acceleration of particles to ultra-relativistic energies in the relativistic jets of GRBs and blazars.

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