

HOW GRAVITATIONAL LENSING HELPS γ -RAY PHOTONS AVOID $\gamma - \gamma$ ABSORPTION

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ABSTRACT

We investigate potential $\gamma - \gamma$ absorption of γ -ray emission from blazars arising from inhomogeneities along the line of sight, beyond the diffuse Extragalactic Background Light (EBL). As plausible sources of excess $\gamma - \gamma$ opacity, we consider (1) foreground galaxies, including cases in which this configuration leads to strong gravitational lensing, (2) individual stars within these foreground galaxies, and (3) individual stars within our own galaxy, which may act as lenses for microlensing events. We found that intervening galaxies close to the line of sight are unlikely to lead to significant excess $\gamma - \gamma$ absorption. This opens up the prospect of detecting lensed gamma-ray blazars at energies above 10 GeV with their gamma-ray spectra effectively only affected by the EBL. The most luminous stars located either in intervening galaxies or in our galaxy provide an environment in which these gamma-rays could, in principle, be significantly absorbed. However, despite a large microlensing probability due to stars located in intervening galaxies, γ -rays avoid absorption by being deflected by the gravitational potentials of such intervening stars to projected distances (“impact parameters”) where the resulting $\gamma - \gamma$ opacities are negligible. Thus, neither of the intervening excess photon fields considered here, provide a substantial source of excess $\gamma - \gamma$ opacity beyond the EBL, even in the case of very close alignments between the background blazar and a foreground star or galaxy.

Key words: galaxies: active – galaxies: jets – gravitational lensing: micro – gravitational lensing: strong

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1. INTRODUCTION

The extragalactic γ -ray sky is dominated by blazars, which are a class of radio-load active galactic nuclei (AGNs) with relativistic jets viewed at small angles with respect to the jet axis. The radiation of blazars is dominated by non-thermal emissions from the jets. The spectral energy distribution of blazars is characterized by two broad components. The low-energy (radio through UV or X-rays) component is produced by the synchrotron radiation of relativistic electrons. The origin of the high-energy (X-rays through γ -rays) component is still under debate, and both leptonic and hadronic scenarios are viable. In leptonic models, the X-ray through γ -ray emission is the result of inverse-Compton radiation with seed photons originating from within the jet (i.e., the synchrotron radiation), or external to the jet, such as from the broad-line region or a dusty torus. In hadronic emission models, the γ -ray emission results from proton synchrotron radiation and photopion-induced cascade processes (for a comprehensive discussion of leptonic and hadronic emission models, see, e.g., Böttcher et al. 2013).

The blazar class is divided into two sub-classes based on the presence or absence of optical and UV emission lines, which are likely correlated with the strength of external photon fields in the blazar environment. Objects exhibiting prominent emission lines have historically been classified as flat spectrum radio quasars (FSRQs) and the presence of a broad-line region implies a significant external radiation field. In the second sub-class, historically classified as BL Lac objects, only weak (Equivalent width $\leq 5 \text{ \AA}$) or no emission lines are typically detected, which provides no evidence for the presence of a substantial broad-line region and, hence, for a strong external radiation field.

γ -rays with energies above a few tens of GeV, produced in relativistic jets, may be substantially affected by interactions

with various photon fields, which cause $\gamma - \gamma$ absorption and electron–positron pair production. The interaction of γ -ray emission with the thermal radiation from the dusty torus, the broad-line region or the accretion disc may produce an imprint in the spectra of blazars (Donea & Protheroe 2003). When the emission region in which γ -rays are produced (often called the “blazar zone”) is located within the broad-line region, the γ -rays have to pass through this intense radiation field dominated by Ly α line emission. As a result, $\gamma - \gamma$ absorption may produce a break in the observed spectra of FSRQs (Poutanen & Stern 2010). The $\gamma - \gamma$ absorption effect is also used to probe the central region of AGNs (Roustazadeh & Böttcher 2011, 2010) and to constrain the location of the γ -ray emitting region (Barnacka et al. 2014b).

γ -ray observations of blazars at energies above 100 GeV are precluded for sources located at large redshift ($z \gtrsim 1$) because of $\gamma - \gamma$ absorption by the Extragalactic Background Light (EBL). In addition to the EBL, overdensities of target photons for $\gamma - \gamma$ absorption may arise if a galaxy is located close to the line of sight between the blazar and the observer. When the center of the intervening galaxy is located at a projected distance of a few kpc from the line of sight, the emission may be split into several paths and can be magnified by strong gravitational lensing.

At high-energy γ -rays (HE: 100 MeV $< E < 100$ GeV), two strongly gravitationally lensed blazars have been observed thus far (Barnacka et al. 2011; Cheung et al. 2014). As has been recently proposed by Barnacka et al. (2014a), gravitationally lensed blazars offer a way to investigate the structure of the jet at high energies and, thus, to locate the site of the γ -ray production within the jet. γ -ray emission from the jets cannot be spatially resolved due to limited angular resolution of current detectors, thus the observations of strongly gravitationally lensed

blazars are very valuable in order to investigate the origin of γ -ray emission of blazars. However, γ -rays produced within relativistic jets of gravitationally lensed blazars have to pass through, or at least in close proximity to, the intervening galaxy on their way to the observer. One might therefore plausibly expect that the infrared–ultraviolet radiation fields of galaxies (or other intervening matter) acting as lenses may lead to excess $\gamma - \gamma$ absorption of the blazar γ -ray emission.

In this paper, we investigate whether observations of gravitationally lensed blazars at energies above 10 GeV are not precluded by $\gamma - \gamma$ absorption. To this aim, in Section 2, we provide a general introduction to the $\gamma - \gamma$ absorption process and a simple estimate of the $\gamma - \gamma$ opacity produced by near-line-of-sight sources in a point-source approximation. In Section 3, we consider the probability of having an intervening galaxy sufficiently close to the line of sight to a background blazar to cause an observable gravitational-lensing effect, and we calculate the $\gamma - \gamma$ opacity due to such a lensing galaxy under realistic assumptions concerning the luminosity, spectrum, and radial brightness profile of the galaxy. In Section 4, we investigate microlensing and γ -ray absorption effects by stars within the intervening galaxy. In Section 5, we consider the chance of observing microlensing effects due to stars within our own Galaxy in the light curves of blazars observed by *Fermi*/LAT. We summarize in Section 6.

2. GAMMA-RAY ABSORPTION

Gamma-ray photons emitted from sources at cosmological distances may be subject to $\gamma - \gamma$ absorption as they travel through various photon fields. The universe is transparent for gamma-ray photons with energy below ~ 10 GeV. Above these energies, the gamma-ray horizon is limited due to absorption by interactions with infrared–ultraviolet radiation fields, composed of integrated light emitted by stars and infrared emissions reprocessed by dust, accumulated throughout the history of the universe. These low-energy photon fields are known as the EBL, and are the subject of extensive studies (Stecker et al. 2006; Aharonian et al. 2006; Bernstein 2007; Franceschini et al. 2008; Finke et al. 2010; Abdo et al. 2010; Ackermann et al. 2012).

The fundamental process responsible for $\gamma - \gamma$ absorption is the interaction with low-energy photons via electron–positron pair production (Gould & Schröder 1967):

$$\gamma_{\text{HE}} + \gamma_{\text{LE}} \rightarrow e^+ + e^-. \quad (1)$$

The threshold condition for the pair production is:

$$\epsilon_{\text{HE}} \epsilon_{\text{LE}} (1 - \cos \theta) > 2 \quad (2)$$

where $\epsilon = hv/(m_e c^2)$ denotes the normalized photon energy, and θ is the interaction angle between the gamma-ray and the low-energy photon. The $\gamma - \gamma$ absorption cross-section has a distinct maximum at \sim twice the threshold energy. Therefore, TeV photons will primarily be absorbed by infrared radiation, with wavelength λ_{LE} estimated by

$$\lambda_{\text{LE}} = 2.4 E_{\text{TeV}} \mu\text{m} \quad (3)$$

The optical depth for photon–photon absorption, $\tau_{\gamma\gamma}$, is given by (Gould & Schröder 1967):

$$\tau_{\gamma\gamma}(\epsilon_{\text{HE}}) = \int dl \int d\Omega (1 - \mu) \int d\epsilon n(\epsilon, \Omega; l) \sigma_{\gamma\gamma}(\epsilon_{\text{HE}}, \epsilon, \mu) \quad (4)$$

where dl is the differential path traveled by the γ -ray photon, $d\Omega = d\phi d\mu$, $\mu = \cos \theta$, $n(\epsilon, \Omega; l)$ is the low energy photon number density, and the $\gamma - \gamma$ absorption cross-section is given by (Jauch & Rohrlich 1976)

$$\sigma_{\gamma\gamma}(\epsilon_1, \epsilon_2, \mu) = \frac{3}{16} \sigma_T (1 - \beta_{\text{cm}}^2) \cdot \left([3 - \beta_{\text{cm}}^4] \ln \left[\frac{1 + \beta_{\text{cm}}}{1 - \beta_{\text{cm}}} \right] - 2\beta_{\text{cm}} [2 - \beta_{\text{cm}}^2] \right) \quad (5)$$

where $\beta_{\text{cm}} = \sqrt{1 - 2/(\epsilon_1 \epsilon_2 [1 - \mu])}$ is the normalized velocity of the newly created electron and positron in the center-of-momentum frame of the $\gamma - \gamma$ absorption interaction.

In addition to diffuse EBL, gamma-rays may suffer from substantial absorption when an intense source of light is close to the line of sight between the source and the observer. Such an intensive source of light may be provided by a foreground galaxy or stars within it, or a star within our own galaxy. For a point source with a narrow (e.g., thermal) photon spectrum peaking at characteristic photon energy, ϵ_s , the differential photon density may be approximated by

$$n(\epsilon_s, \Omega; l) = \frac{L}{4\pi x^2 c \epsilon_s^2 m_e c^2} \delta(\Omega - \Omega_s), \quad (6)$$

where L is the total luminosity of the source, x is the distance between the source and any given point along the gamma-ray path, and Ω_s describes the solid angle in the direction toward the source from that point. For a simple estimate, we use a δ function approximation to the $\gamma - \gamma$ absorption cross-section, $\sigma_{\gamma\gamma}(\epsilon_1 \epsilon_2) \approx (\sigma_T/3) \epsilon_1 \delta(\epsilon_1 - 2/\epsilon_2)$. If the impact parameter of the γ -ray path (i.e., the distance of closest approach to the source) is b , and we define $l = 0$ as the point of closest approach, then $x = \sqrt{b^2 + l^2}$ and $\mu = l/x$. With these simplifications, the integration in Equation (4) can be evaluated analytically to yield an estimate for the $\gamma - \gamma$ optical depth at a characteristic γ -ray energy of $E_\gamma = 520 E_{\text{eV}}^{-1}$ GeV (where E_{eV} is the target photon energy in units of eV):

$$\tau_{\gamma\gamma}(E_\gamma) \approx \frac{\sigma_T L}{6 c m_e c^2 \epsilon_s b} = 3 \times 10^{-9} \left(\frac{L}{L_\odot} \right) E_{\text{eV}}^{-1} b_{\text{pc}}^{-1}, \quad (7)$$

where b_{pc} is b in units of pc. Conversely, we can use Equation (7) to define a “ $\gamma - \gamma$ absorption sphere” of radius r_{abs} within which the line of sight would need to pass a source for γ -rays to experience substantial ($\tau_{\gamma\gamma} > 1$) $\gamma - \gamma$ absorption:

$$r_{\text{abs}} \sim 10^9 \left(\frac{L}{L_\odot} \right) E_{\text{eV}}^{-1} \text{cm} \sim 73 \left(\frac{L}{L_*} \right) E_{\text{eV}}^{-1} \text{pc}, \quad (8)$$

where the latter estimate assumes a characteristic luminosity of a galaxy, $L_* = 2.4 \times 10^{10} L_\odot$. Equation (8) suggests that only the most massive stars are capable of causing significant $\gamma - \gamma$ absorption individually, which will be confirmed with more detailed calculations in Section 4. For entire galaxies, typically the $\gamma - \gamma$ absorption sphere, as evaluated by Equation (8) is smaller than the galaxy itself, which means that the line of sight would need to pass through the galaxy (in which case, of course, our approximation of the galaxy as a point source becomes invalid). The case of $\gamma - \gamma$ absorption by intervening galaxies will be considered with more detailed calculations in Section 3.

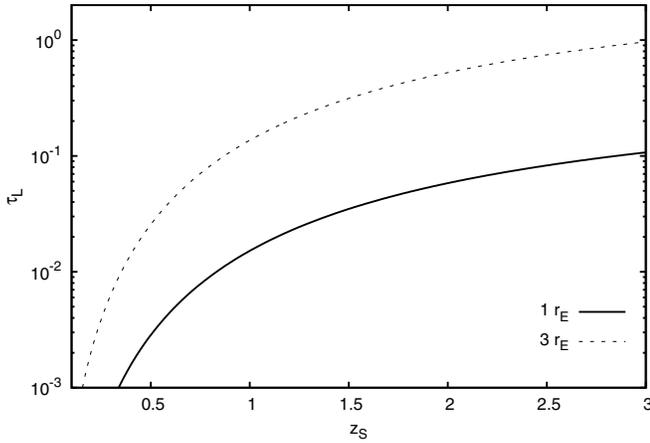


Figure 1. Total lensing optical depth, τ_L , as a function of the redshift of the source, z_s . The curves show the optical depth accounting for the lenses within $1 r_E$ (solid) and within $3 r_E$ (dashed).

3. INTERVENING GALAXIES

Let us now consider the effect of an intervening galaxy close to the line of sight between an observer and a blazar. When the projected distance between the lens and the source, in the lens plane, is of the order of a few kpc or less, strong lensing phenomena are expected. A critical parameter determining lensing effects is the Einstein radius, defined as:

$$r_E = \theta_E \times D_{OL} = \sqrt{\frac{4GM}{c^2} D} \approx 5 \text{ kpc} \left(\frac{D}{1 \text{ Gpc}} \right)^{\frac{1}{2}} \left(\frac{M}{10^{11} M_\odot} \right)^{\frac{1}{2}}, \quad (9)$$

where $D = D_{OL} D_{LS} / D_{OS}$, D_{OL} , D_{LS} , and D_{OS} are the angular diameter distances from the observer to the lens, from the lens to the source and from the observer to the source, respectively (Narayan & Bartelmann 1996; Schneider et al. 1992; Barnacka 2013), and we have scaled the expression to the typical mass of a lensing galaxy, $\sim 10^{11} M_\odot$.

The chance of lensing by an object like a galaxy or a star within the galaxy can be expressed in terms of the lensing optical depth, τ_L , which is a measure of the probability that at any instance in time a lens is within an angle $n \times \theta_E$ of a source:

$$\tau_L(D_{OS}) = \frac{\pi n^2}{d\Omega} \int dV_L \int dM \rho_L(M, D_{OL}) \theta_E^2(M, D), \quad (10)$$

where n denotes the number of Einstein radii in which we are looking for a potential lens, $dV_L = d\Omega D_{OL}^2 dD_{OL}$ is a differential volume element on a shell with radius D_{OL} covering a solid angle $d\Omega$, and $\rho_L(M, D_{OL})$ is the number density of potential lenses (Schneider et al. 1992).

Figure 1 shows the total optical depth as a function of the redshift of the source. The calculations are based on a homogeneous Friedmann–Lemaître–Robertson–Walker cosmology, with Hubble constant, $H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$, mean mass density, $\Omega_M = 0.315$, and the normalized cosmological constant, $\Omega_\Lambda = 0.686$ (Planck Collaboration et al. 2013). When the lensing optical depth is small, it can be identified with the probability of a background galaxy being located within n Einstein radii from the center of mass of a foreground galaxy.

Barnacka (2013) has estimated a number of expected strongly, gravitationally lensed systems among 370 FSRQs listed in the 2nd Fermi catalog (Nolan et al. 2012). In the sample of these 370 FSRQs, the expected number of sources with at least one intervening galaxy within one Einstein radius was estimated to be ~ 10 .

Therefore, on average, 3% of FSRQs detected by the *Fermi*/LAT have a galaxy located within a projected distance smaller than one Einstein radius (~ 5 kpc). Extrapolating this result to the distance of $3 \times r_E$, one can expect that on average $\sim 30\%$ of gamma-ray blazars will have an intervening galaxy within a distance smaller than 15 kpc, i.e., within $3 \times r_E$. For any given blazar, the number of foreground galaxies, within a certain distance from the line of sight, depends on the redshift of the source (see Figure 1).

The projected distance, r_S , in the foreground galaxy plane, is defined as the distance between the center of mass of a foreground galaxy and the line of sight between the emitting region of the source and the observer. When the system satisfies the condition that r_S is larger than r_E , one is in the weak lensing regime (Schneider 2005; Bartelmann & Schneider 2001). In this regime, the morphology of the image is slightly deformed and may be displaced, but in general there is only one image of the source, lensing magnification is negligible, and therefore the light curve of a source remains unaffected.

On the contrary, when r_S is smaller than r_E , the light is split into several paths and the images may be significantly magnified. The position and magnification of images change with r_S . When a mass distribution of a lens is well-represented by a singular isothermal sphere (SIS), there are two images. A third image has zero flux, and can therefore be ignored.

The positions of the images are at $r_\pm = r_S \pm r_E$ (Narayan & Bartelmann 1996). When r_S approaches r_E , the r_+ image appears beyond r_E ; at the same time, r_- moves toward the center of the lens. The light of the image at r_- will take a path closer to the center of the galaxy, where one could suspect that $\gamma - \gamma$ absorption in the radiation field of the lensing galaxy may be non-negligible.

The magnification of lensed images is given as $A_\pm = r_\pm / r_S$. When image, r_- , appears closer to the center of the lens, its magnification decreases, so that emission from these images become negligible in the limit of very small distances from the center. On the contrary, the second image is further deflected from the center of the lens, and is strongly magnified. Therefore, lensed images with significant magnification will pass the galaxy at large distances where $\gamma - \gamma$ absorption might be negligible.

In order to assess whether $\gamma - \gamma$ absorption by a lensing galaxy might be important, the corresponding opacity, $\tau_{\gamma\gamma}$, needs to be evaluated. As pointed out in Section 2, the point source approximation used to derive the estimate in Equation (7) is not valid for impact parameters of the order of (or smaller than) the effective radius of the galaxy. We therefore, evaluate the integral in Equation (4) numerically, properly accounting for the angular dependence of the extended radiation field of the galaxy $n(\epsilon, \Omega; l)$. For this purpose, we approximate the galaxy as a flat disk with a De Vaucouleurs surface brightness profile. The disk normal vector is inclined with respect to the line of sight by an inclination angle, i , and the local disk spectrum is characterized by a blackbody at a characteristic temperature of $T = 6000$ K. Details of the evaluation of the $\gamma\gamma$ opacity can be found in the Appendix.

Figure 2 shows the resulting $\gamma - \gamma$ opacity for gamma-ray photons passing through a Milky-Way-like galaxy ($L = L_*$,

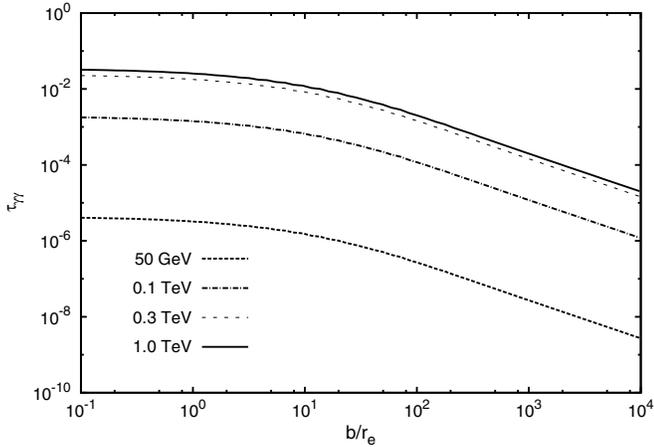


Figure 2. $\gamma - \gamma$ opacity as a function of impact parameter, b , of the (assumed undeflected) γ -ray path from the center of the galaxy, for various γ -ray energies. The galaxy is assumed to be a Milky-Way-like galaxy with an effective radius of $r_e = 0.7$ kpc, intercepted at an inclination angle of $i = 30^\circ$, a temperature of $T = 6000$ K, and a luminosity of $L = L_*$.

$r_e = 0.7$ kpc), as a function of the impact parameter, b , for various gamma-ray energies. The results are shown for an inclination angle of $i = 30^\circ$, but we find that they are only very weakly dependent on i . The figure illustrates that for such a case, $\gamma - \gamma$ absorption within the collective radiation field of an individual, intervening galaxy is negligible, irrespective of the gamma-ray's impact parameter. We note that for $b \gg r_e$, where the galaxy may reasonably be approximated by a point source, our results are in excellent agreement with the analytical estimate of Equation (7). At smaller impact parameters, the $\gamma\gamma$ opacity is dominated by the local radiation field around the impact point of the γ -ray trajectory on the disk, which is substantially smaller than the one resulting from the point-source approximation (i.e., assuming that the luminosity of the entire galaxy emanates from the center of the galaxy). Therefore, the $\gamma\gamma$ opacity is smaller than predicted by the point-source approximation.

Obviously, the $\gamma - \gamma$ opacity scales linearly with the galaxy's luminosity, so given the same radial profile (with $r_e = 0.7$ kpc), a luminosity of $L \gtrsim 10 L_*$ would be required to cause significant $\gamma - \gamma$ absorption.

Figure 3 shows the $\gamma - \gamma$ opacity due to an L_* galaxy, assuming an effective radius of $r = 0.1$ kpc. As expected, the maximum opacity (for small impact parameters) increases with increasing compactness of the galaxy. However, even for this case, a large luminosity of $L \gtrsim L_*$ (combined with very small size) would be required to lead to substantial $\gamma - \gamma$ absorption. However, galaxies of such luminosities are typically giant ellipticals or large spirals with substantially larger effective radii than 1 kpc. We may therefore conclude that, in any realistic lensing situation, $\gamma - \gamma$ absorption due to the collective radiation field of the galaxy is expected to be negligible.

4. MICROLENSING STARS WITHIN THE INTERVENING GALAXY

When gamma-rays emitted by a source at a cosmological distance (e.g., a blazar) crosses the plane of an intervening galaxy, they pass a region with an over density of stars and therefore have a non-negligible probability of passing near the $\gamma - \gamma$ absorption sphere of a star, as estimated by Equation (8).

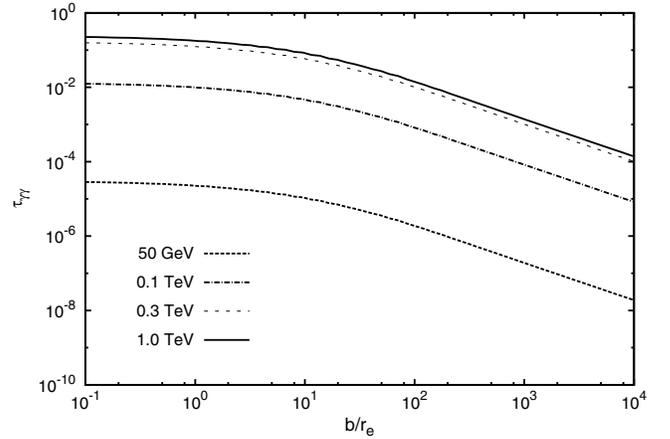


Figure 3. Same as Figure 2, but for an effective radius of $r_e = 0.1$ kpc.

This suggests that they may suffer non-negligible $\gamma - \gamma$ absorption.

For a more detailed evaluation of the $\gamma - \gamma$ opacity as a function of γ -ray photon energy, ϵ_{HE} , and impact parameter, b , we have evaluated $\tau_{\gamma\gamma}(\epsilon_{\text{HE}})$ numerically. This is done by numerically carrying out the integrations in Equation (4) under a point source approximation, as discussed in Section 2, representing the stellar spectrum as a blackbody with characteristic temperature and luminosity determined by the spectral type of the star, and using the full $\gamma - \gamma$ absorption cross-section (Equation 5).

Figure 4 shows the optical depth for $\gamma - \gamma$ absorption as a function of the impact parameter, i.e., distance of closest approach to the center of the star, for various γ -ray photon energies, for a sun-like (G2V) and a very massive (O5V) star. In both figures, the curves begin at the radius of the star. The figure illustrates that for a sun-like star, no significant $\gamma - \gamma$ absorption is expected for any line of sight that does not pass through the star. We find that the same conclusion holds for all stars with spectral type F0 or later (i.e., less massive and cooler). For A-type stars, $\gamma - \gamma$ absorption (though still with maximum $\tau_{\gamma\gamma} < 1$) can occur if the line of sight passes within a few stellar radii from the surface of the star. Significant $\gamma - \gamma$ absorption (with $\tau_{\gamma\gamma}^{\text{max}} > 1$) can occur for more massive (O and B) stars, within a few tens to hundreds of stellar radii. The right panel of Figure 4 illustrates that significant $\gamma - \gamma$ absorption by an O-type star can occur for impact parameters up to $\sim 10^{15}$ cm from the center of the star. We note that the results of our numerical calculations are in excellent agreement with the back-of-the-envelope estimate provided in Equation (7).

The calculations presented above assume straight photon paths, unaffected by gravitational lensing. The deflection of the light-rays by the stars in the foreground lens galaxy, the so-called microlensing effect, has been widely elaborated (Paczynski 1986; Kayser et al. 1986; Irwin et al. 1989; Kochanek et al. 2007). Given the small deflection angles expected from microlensing, our calculations of $\tau_{\gamma\gamma}$ are still expected to be accurate, as long as a proper value for the impact parameter b is used that takes into account the microlensing effect. It is known that the probability of microlensing of gravitationally lensed quasars by the stars in the foreground lens galaxy is one (Wambsganss 2006), which means that γ -rays are likely to pass through the Einstein radius of many stars before escaping from the galaxy.

The Einstein radius of a star located at cosmological distances is of the order of $r_E \sim 5 \times 10^{16} (M/M_\odot)^{1/2}$ cm (see Equation 9). The radii of main-sequence stars range from $\sim 10^{10}$ – 10^{12} cm,

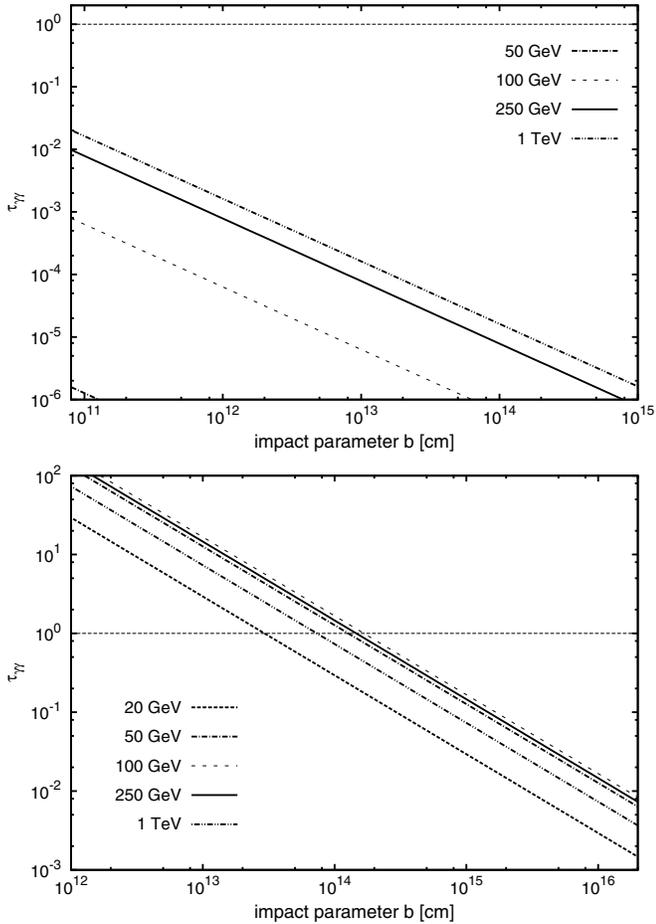


Figure 4. Optical depth for $\gamma - \gamma$ absorption, $\tau_{\gamma\gamma}(E_\gamma)$ as a function of the impact parameter, measured from the centers of star. Stellar luminosities, blackbody temperatures, and radii are chosen corresponding to a G2-type main-sequence star (left) and an O5-type main-sequence star (right). All curves start at the stellar radius and are labeled by the respective γ -ray energy, E_γ .

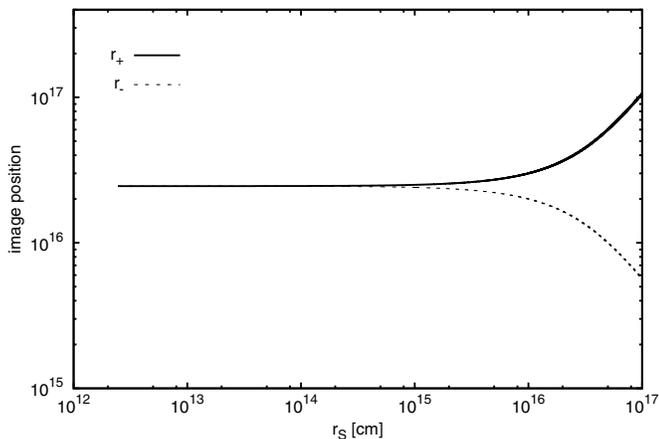


Figure 5. Distance of the lensed images, r_+ and r_- , from the center of the lens as a function of the projected distance r_S between the source and the lens. The source is at redshift $z_S = 0.6$, and lens at redshift $z_L = 0.4$. The lens is assumed to have a mass of $M_{\text{lens}} = 1 M_\odot$.

which is much smaller than r_E . Therefore, the mass distribution of the lens is well-approximated by a point mass.

Figure 5 shows the positions r_\pm of the lensed images of a background source, as a function of the distance between a source and a lens, b , in the lens plane. Both the source and the lens have been assumed to be point-like, resulting in two source

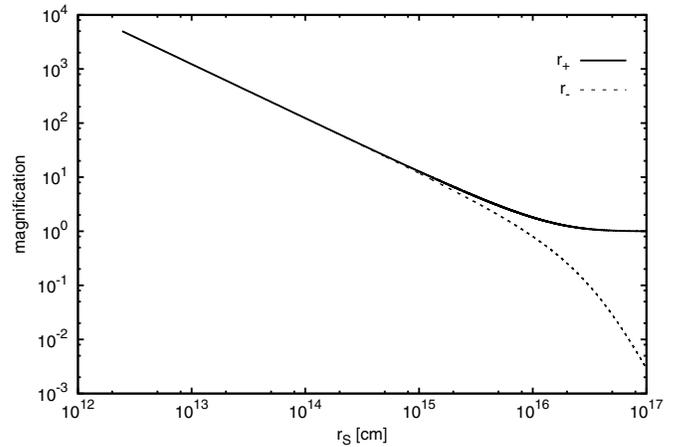


Figure 6. Magnification of the lensed images as a function of the projected distance between the source and the lens, r_S , in the lens plane, for the same parameters as used in Figure 5.

images at positions r_\pm . The lens has a mass of $M_{\text{lens}} = 1 M_\odot$. The figure illustrates that for very small projected distances, b , both images appear at $r_\pm \sim 2.5 \times 10^{16}$ cm, which implies that both lines of sight pass the star far outside the γ -ray absorption sphere. Only for projected distances near the Einstein radius does one of the images (at r_-) appear at smaller distances from the star. Figure 6 shows the magnification of the lensed images for this case. This figure shows that, when the r_- image appears at small separations from the lens, it will be strongly demagnified and, thus, any modulation of this image by $\gamma - \gamma$ absorption will remain undetectable, while the outer, essentially unmagnified image will remain unaffected by $\gamma - \gamma$ absorption due to its large impact parameter from the star.

An additional factor playing into the consideration of potential lensing and $\gamma\gamma$ absorption effects, is the apparent size of the γ -ray source on the plane of the sky. The sizes of γ -ray sources can generally be constrained based on causality arguments, from the minimum variability time scale, which typically yields sizes of the order of 10^{16} cm (Sbarrato et al. 2011) at the distance of the source. The size of such a source projected onto the lens planes is D_{OS}/D_{OL} times larger. Thus, the projected size of the γ -ray emitting region is comparable to the size of the Einstein radius of a solar-mass-sized lens. Therefore, the source will appear extended in the plane of the lens, and will probe a multitude of sightlines around the lens but no matter which sightline any individual γ -ray photon will follow, gravitational lensing will always cause the photon to avoid the γ -ray absorption sphere of the lens.

As a result, gamma-rays that travel cosmological distances and pass through galaxies with over-densities of stars, will not suffer substantial $\gamma - \gamma$ absorption because γ -rays will be deflected to the distances far beyond the γ -ray absorption radius around any individual star in the intervening galaxy.

Light traces matter, with the relation between sources of light and of space-time curvature being determined by the mass-to-light ratio M/L of any given source. Thus, our considerations suggest that for any sources of light with similar (or larger) M/L as the sources considered here (i.e., stars or galaxies), gravitational lensing will always aid in avoiding $\gamma - \gamma$ absorption by intervening light sources at cosmological distances.

5. MICROLENSING STARS WITHIN THE MILKY WAY

We finally consider the microlensing effects in the light curves of blazars produced by stars in our own Galaxy. In this case,

the Einstein radius of solar mass stars is of the order of a few $\times 10^{13} (M/M_\odot)^{1/2}$ cm, i.e., smaller by a factor of ~ 1000 compared to cosmological lenses, due to their smaller distance. This has an impact on the lensing optical depth, τ , which for Galactic microlensing is of the order of 10^{-6} . The duration of a microlensing event is given by the time required for the lens to move by $2r_E$ relative to the line of sight to the background source. With typical Galactic speeds of $v \sim 200 \text{ km s}^{-1}$, the time scale of typical Galactic microlensing events is $t_0 \sim 130 \text{ days} \times (M/M_\odot)^{1/2}$.

For the purpose of a rough estimate, let us assume that all lensing objects have the same mass and the same velocity. Then the number of microlensing events, N , that may be expected if n_S sources are monitored over a time interval Δt , can then be estimated as

$$N = \frac{2}{\pi} n_S \tau \frac{\Delta t}{t_0}. \quad (11)$$

The *Fermi* satellite has monitored the entire sky since 2008 August, corresponding to $\Delta t \sim 2000$ days. The observations performed over the first five years of its operation resulted in the detection of ~ 1000 objects. Using these estimates, the number of expected microlensing events in the light curves of objects monitored by *Fermi*/LAT is of the order of 10^{-3} . Therefore, microlensing effects by stars located in our Galaxy are extremely rare. The $\gamma\gamma$ absorption radius of a star in our Galaxy is still substantially smaller than r_e for low-mass stars, and comparable to r_e for the most massive stars. The same conclusion therefore holds for potential $\gamma\gamma$ absorption effects from intervening stars in our Galaxy, so that γ -rays can travel freely through our Galaxy without lensing deflection and/or $\gamma\gamma$ absorption by stars.

6. SUMMARY

Blazars are the most luminous (non-transient) sources detected up to large cosmological distances. The lensing probability for these luminous and distant sources is thus significant: of the order of a few percents for sources observed in the energy range from 100 MeV to 300 GeV. The gravitational lensing by intervening galaxies and individual stars within these lensing galaxies may lead to repeating γ -ray light curve patterns due to the time delay between the lensed images of the blazar. The measurement of these time delays and magnification ratios between the flaring episodes of the given blazars can be exploited to ascertain the location of the γ -ray emitting regions within the blazars (Barnacka et al. 2014a).

In this paper, we have investigated whether the light emitted by the foreground lenses may affect the lensing signatures due to $\gamma - \gamma$ absorption. We found that the collective photon fields from lensing galaxies are not expected to produce any measurable excess $\gamma - \gamma$ opacity beyond that of the EBL, and that microlensing and $\gamma - \gamma$ absorption by stars within our own galaxy is extremely unlikely to affect any *Fermi*/LAT detected γ -ray blazars. Our most intriguing result is that microlensing stars within intervening galaxies are not expected to lead to significant excess $\gamma - \gamma$ absorption either, as the gravitational lensing effect will always cause the light paths reaching the Earth to be deflected around the source of excess light, keeping them at distances from the star, at which $\gamma - \gamma$ absorption remains negligible.

Consequently, we have demonstrated that light curve studies of gravitationally lensed blazars are a promising avenue for revealing the structure of the γ -ray emitting region in blazars,

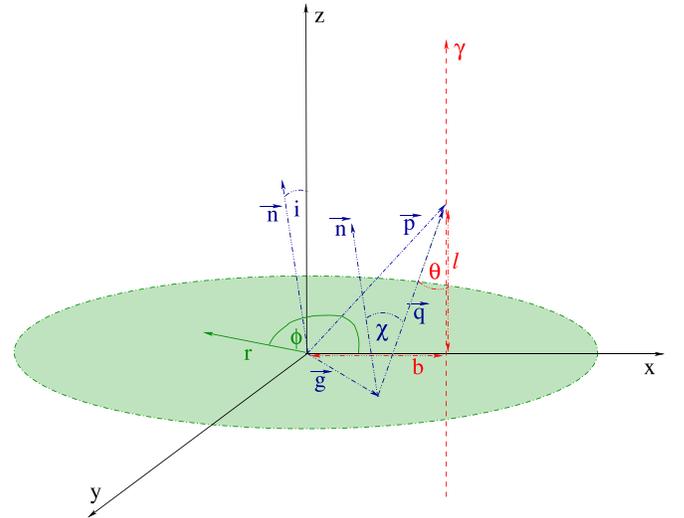


Figure 7. Geometry used for the calculation of the $\gamma - \gamma$ opacity due to the radiation field of a lensing galaxy.

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

and that excess $\gamma - \gamma$ absorption by the radiation fields of gravitational lenses will not interfere with γ -ray lensing studies. As such, the magnification ratio between echo flares in the light curve is not affected by the $\gamma - \gamma$ absorption and future observations of blazars at energies above 10 GeV with experiments like VERITAS (Weekes et al. 2002) or CTA (Actis et al. 2011) are not precluded by γ -ray absorption.

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APPENDIX

This Appendix provides details of the calculation of the $\gamma\gamma$ opacity due to an intervening (macrolensing) galaxy. The galaxy is approximated as a flat disk with a De Vaucouleurs surface brightness profile:

$$F(r) = F_0 e^{-a[(r/r_e)^{1/4} - 1]}, \quad (A1)$$

where $a = 3.33$, r_e is the effective radius of the galactic bulge, and F_0 can be related to the total luminosity L of the galaxy through $F_0 \approx 2.14 \times 10^{-3} L/r_e^2$. The spectrum of the galaxy is approximated by a blackbody radiation field with temperature $T = \Theta m_e c^2/k$, so that the spectral disk flux as is represented as

$$F_\epsilon(r) = K e^{-a[(r/r_e)^{1/4} - 1]} \frac{\epsilon^3}{e^{\epsilon/\Theta} - 1} \quad (A2)$$

with $K = \pi^4 F_0/(15\Theta^4)$.

Figure 7 illustrates the geometry adopted for the calculation of $\tau_{\gamma\gamma}$. We chose the direction of propagation of the γ -ray as the z axis, and the x axis is defined by the radius vector from the center

of the galaxy to the impact point of the γ -ray trajectory on the galactic disk, at distance b (the impact parameter). The normal vector of the galactic disk is inclined with respect to the z axis by the inclination angle i . The integration over the galactic disk is carried out in polar co-ordinates with the angle ϕ measured from the x axis. The photon propagation length $l = 0$ is defined as the photon's impact point on the disk. \mathbf{g} denotes the radial vector from the center of the galaxy to any given point (r, ϕ) on the disk, \mathbf{p} is the vector from the center to the current location of the γ -ray photon, and $\mathbf{q} = \mathbf{p} - \mathbf{g}$ is the vector connecting any point on the disk to the location of the γ -ray photon, whose length can be calculated as

$$q = \sqrt{r^2 + l^2 + b^2 - 2rb \cos \phi - 2rl \sin \phi \sin i} \quad (\text{A3})$$

The $\gamma\gamma$ interaction angle cosine is then given by $\mu = \cos \theta = q_z/q = (l - r \sin \phi \sin i)/q$. Finally, we note that the solid angle element $d\Omega$ can be re-written by considering the projected disk surface element: $q^2 d\Omega = |\cos \chi| r dr d\phi$, where χ is the angle between \mathbf{q} and the disk normal, $\mathbf{n} = (0, \sin i, \cos i)$:

$$\cos \chi = \frac{2r \sin \phi \cos i \sin i - l \cos i}{q} \quad (\text{A4})$$

which allows us to replace the $d\Omega$ integration by an integration over the disk surface, $r dr d\phi$. Thus, the $\gamma\gamma$ opacity is calculated as

$$\begin{aligned} \tau_{\gamma\gamma}(\epsilon_{\text{HE}}) &= \frac{K}{4\pi m_e c^3} \int_{-\infty}^{\infty} dl \int_r^{\infty} r dr e^{-a\left(\left[\frac{r}{r_e}\right]^{1/4} - 1\right)} \\ &\cdot \int_0^{2\pi} d\phi (1 - \mu) \frac{|\cos \chi|}{q^2} \int_{\frac{2}{\epsilon_{\text{HE}}(1-\mu)}}^{\infty} d\epsilon \frac{\epsilon^2}{e^{\epsilon/\Theta} - 1} \sigma_{\gamma\gamma}(\epsilon_{\text{HE}}, \epsilon, \mu). \end{aligned} \quad (\text{A5})$$

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