PROCEEDINGS OF SCIENCE

Gravitational light bending prevents gamma-gamma absorption in gravitational lenses

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The magnification effect due to gravitational lensing enhances the chances of detecting moderate-redshift ($z \sim 1$) sources in very-high energy (VHE; $E > 100\,\mathrm{GeV}$) γ-rays by ground-based Atmospheric Cherenkov Telescope facilities. It has been shown in previous work that this prospect is not hampered by potential γ-γ absorption effects by the intervening (lensing) galaxy, nor by any individual star within the intervening galaxy. In this paper, we expand this study to simulate the light bending effect of a realistic ensemble of stars. We first demonstrate that, for realistic parameters of the galaxy's star field, it is extremely unlikely (probability $\leq 10^{-6}$) that the direct line of sight between the γ-ray source and the observer passes by any star in the field close enough to be subject to significant $\gamma\gamma$ absorption. Our simulations then focus on the rare cases where $\gamma\gamma$ absorption by (at least) one individual star might be non-negligible. We show that gravitational light bending will have the effect of avoiding the γ-γ absorption spheres around massive stars in the intervening galaxy. This re-inforces prospects of using VHE γ-ray observations of lensed blazars to probe the location of the γ-ray emission region in those blazars.

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1. Introduction

Very-high energy (VHE; $E > 100\,\text{GeV}$) γ-rays are subject to γ-γ absorption from extragalactic background light (EBL) due to electron-positron pair production. The γ-γ absorption effect is further intensified by the dense infrared-optical-UV radiation fields from various celestial objects. The distance at which VHE γ-rays can be detected from sources such as blazars is thus greatly reduced compared to lower energy radiation. As such, VHE γ-ray sources at large cosmological distances are required to be exceptionally bright. However, the magnification effect from gravitational lensing by intervening galaxies may extend the VHE γ-ray visibility of lensed sources to signigicantly larger distances. The most distant source of VHE γ-rays to date is the gravitationally-lensed blazar S3 0218 + 357 [3] at redshift $z = 0.944$.

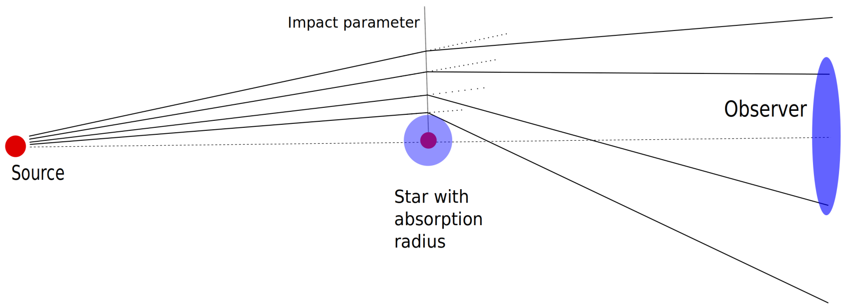


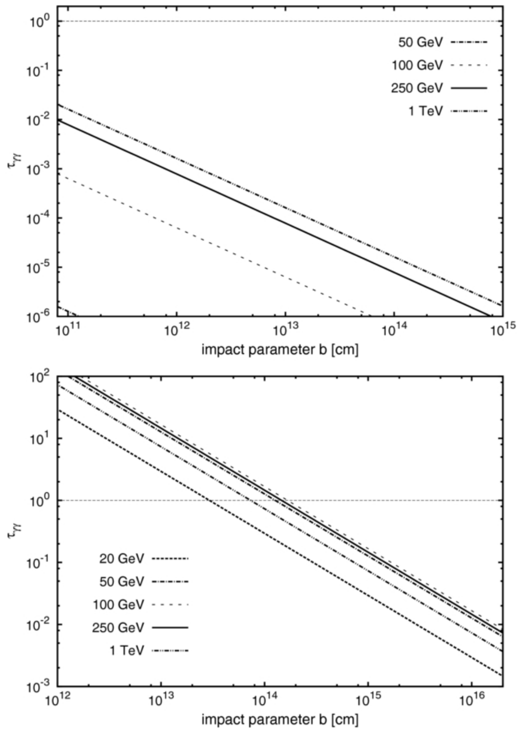
Figure 1: Schematic representation of γ-rays (black solid lines) being lensed around a star. The absorption radius of the star as blue shaded circle.

In the context of a potential VHE detection of a gravitationally-lensed blazar, it is critical to understand whether the additional infrared-optical-UV radiation fields from a lensing galaxy contribute significantly to γ-γ absorption of VHE γ-rays which could effectively nullify the brightness enhancements from gravitational lensing. [1] showed that there is no significant contribution to γ-γ absorption from an individual intervening star or the collective radiation field of the entire galaxy. Due to the gravitational light bending, γ-rays will pass these objects at distances much larger than $r_{\gamma\gamma}$[1].

Figure 2 illustrates that the γ-γ opacity is negligible even if γ-rays pass through a galaxy. As when considering the effet of an entire galaxy, the point source approximation is no longer valid, the galaxy has been represented as a continuous disc with a de Vaucouleur brightness profile in [1]. This neglects the lensing and potential γ-γ absorption effects of individual stars within the galaxy, which could possibly greatly exceed the effects found with a continuous approximation of the galaxy's gravitational and radiation field.

We therefore here extend the study of possible γ-γ absorption effects in gravitational lenses when γ-rays pass through an intervening galaxy, taking into account the contribution from a realistic ensemble of individual stars within the galaxy. This is done by simulating a representative collection of stars in a galaxy and tracing γ-ray paths passing through it. We then evaluate the point

[1] the radial distance at which the γ-γ opacity becomes significant; $\tau_{\gamma\gamma} > 1$.



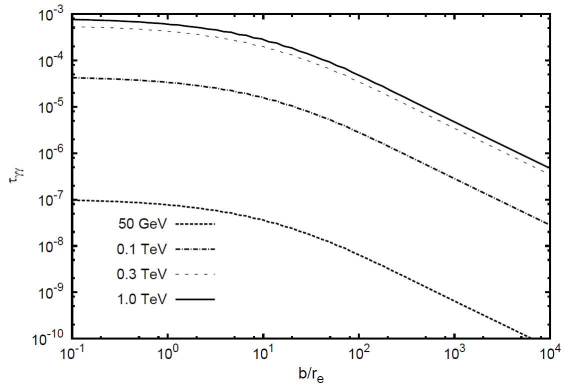


Figure 2: Left: Due to gravitiational light beniding, γ-rays will pass these stars at charactersistic minimum distances of $10^{16}-10^{17}$cm, i.e., far outside the stars' γ-γ absorption radii.
Right: γ-γ opacity as function of impact parameter of γ-rays from Milky-Way like galaxy with effective radius $r_e = 0.7\,$pc.
[1]

of closest approach of the γ-rays to each star and compare it to the radii of γ-γ absorption spheres within which significant absorption occurs.

A short summary of the numerical scheme and results are presented in the following sections. Details are described in [2].

2. Numerical Setup

The geometrical setup is identical to the schematic in Figure 3. The source, intervening galaxy and observer are collinearly aligned. The disc of the galaxy is seen face-on by the observer. Both the source and the observer are assumed to be a distance of 3 Gpc from the lensing galaxy.

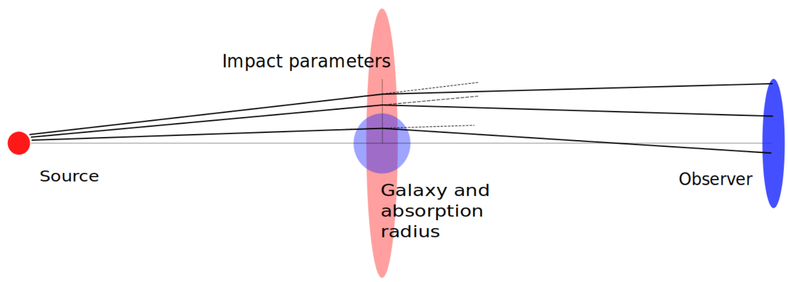


Figure 3: Schematic representation of γ-rays passing through a galaxy (red shaded disc). The absorption radius of a galaxy (blue shaded circle) as calculated with point source approximation is typically smaller than the galaxy itself.

Large lensing deflections will result in γ-rays missing the observer which render the γ-ray path irrelevant. Such deflections are highly unlikely to be realigned by deflections from other stars.

Based on the expectation that observed γ-rays will only experience small deflections the simulation volume is restricted to a cylinder parallel to the direct line of sight with radius $r = 10\,\mathrm{ly}$ and height $h = 1\,\mathrm{kpc}$, comparable to the scale height of a typical galaxy. The expected small-angle deflections justify the approximation of the lensing effect by instantaneous deflections of the γ-ray path by a deflection angle, α

$$\alpha = \frac{4GM}{c^2 b} \tag{2.1}$$

Where G is the universal gravitational constant, M the mass of the star, c the speed of light and b the impact parameter (distance of closest approach).

The volumetric star distribution is assumed to be uniform with an average stellar density of $n = 10^{-2}\ \mathrm{ly}^{-3}$. The mass distribution is calculated with the Salpeter initial mass fucntion ($N(M) \propto M^{-2.5}$).

Low mass stars ($M \leq 1M_\odot$) do not lead to significant absorption unless the γ-ray pass through the star [1]. Their deflections are also considered to be small enough to ignore. The mass range of the stars used in the simulation then spans $1\ M_\odot \leq M \leq 100\ M_\odot$.[2] This justifies the reduction of the amount of stars in the simulation to only 250 for the specific volume.

[2] show that the probability of finding a star which could cause significant absorption on the direct line of sight is $P \lesssim 10^{-6}$. There is thus little risk for a VHE γ-ray travelling along the direct line of sight to pass close enough to a star to be absorbed. For the simulations a star is deliberately placed in the line of sight to test the unlikely worst case.

The simulation employs Monte Carlo methods to generate a star profile and then traces the path of a grid of entry positions and directions for the γ-rays through the star profile. The path impact parameters are then calculated and normalised to $r_{\gamma\gamma}$ of each individual star.

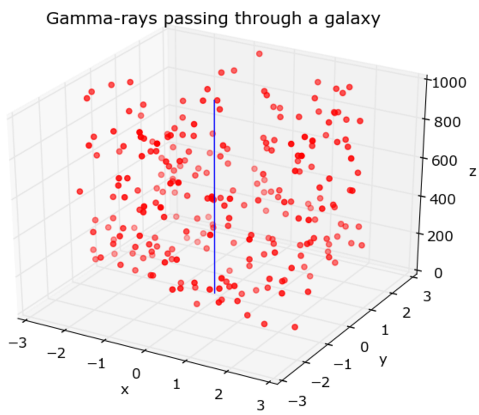


Figure 4: Visual representation of an observed γ-ray path (blue line) traced through a collection of stars (red dots). The axes are in units of parsec. [2].

Figure 4 shows the path of a single γ-ray initially travelling along the line of sight through a collection of stars as demonstration of the concept.

[2] The initial mass range being $0.08M_\odot \leq M \leq 100M_\odot$

3. Results

Figure 5 shows the comparison between the impact parameters (normalised to $r_{\gamma\gamma}$) for all of the 250 stars in a representative simulation, of a lensed and unaffected observed γ-ray photon initially travelling along the direct line of sight.

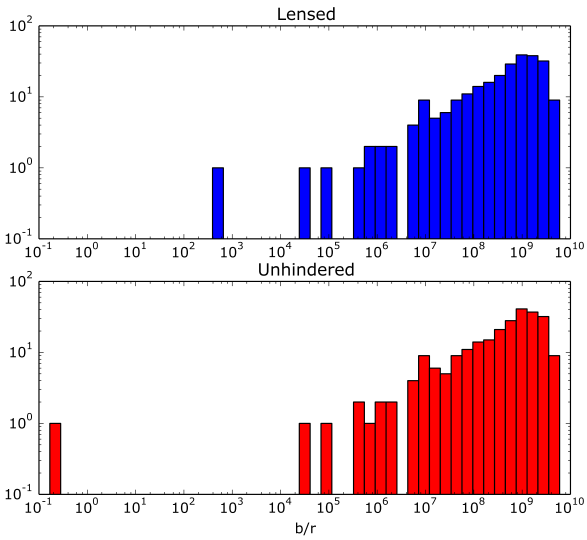


Figure 5: Histograms of results comparing the normalised impact parameters (b/r) of line of sight (red) to a lensed γ-ray (blue). Data from [2].

The intervening star which has been placed deliberately close to the direct line of sight, is immediately apparent in the histogram of the undeflected γ-ray. The lensed γ-ray has clearly been deflected around this deliberately placed star and avoided the region of significant $\tau_{\gamma\gamma}$. The absolute minimum normalised impact parameter of the γ-ray path is about 3 orders of magnitude larger than that of the direct line of sight.

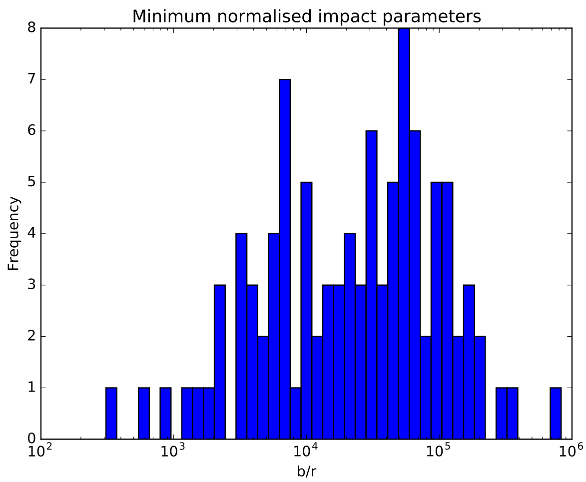


Figure 6: Histogram for the minimum impact parameters for 100 simulations. Data from [2].

In order to test the robustness of the result presented in Figure 5, we preformed 100 simulations with different random realizations of stellar distributions. Figure 6 shows a histogram of the absolute minimum normalised impact parameter of all the observed γ-rays of each individual simulation.

This shows that none of the observed γ-rays passed through low energy radiation fields that could cause significant absorption beyond that of the EBL. This implies that gravitational lenses do not contribute to γ-γ absorption.

Globular clusters and O/B associations were added into the simulations to improve their realism. Both cases yielded results identical to Figure 6. All these results confirm that the findings of [1] hold for a representative collection of stars in a galaxy.

There is the possibility that supermassive black holes (SMBH) in the centres of intervening galaxies or intermediate-mass black holes may significantly affect both the path and the possible γ-γ absorption within the lens. Given the very small ration of SMBH to total mass, the gravitational effect of the SMBH is expected to play a significant role only within the central few 100 pc from the SMBH. If a γ-ray passes within such a small distance of a SMBH, a posible acreation disk and/or broad-line-region radiation field (uf tge SMBH is actively accreting) may cause significant γ-γ absorption. Such effects have been neglected in this study, assuming that the lensed γ-ray path passes far-enough from an active SMBH in the galactic center not to be significantly affected by it.

4. Summary

We investigated the claim of [1] that gravitationally lensed VHE γ-rays avoid γ-γ absorption regions within the lens itself and are not subject to excessive γ-γ absorption even in the case where γ-rays pass through a galaxy. By means of ray-tracing simulations, we demonstrated that this result still holds when taking into account a realistic ensemble of stars within the intervening galaxy.

This re-inforces the prospects for future VHE γ-ray dtections of gravitationally-lensed blazars at large distances.

References

[1] A. Barnacka, M. Böttcher, and Iu. Sushch. *How gravitational lensing helps γ-ray photons avoid γ-γ absorption*. *ApJ*, 790, 147, 2014.

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[3] C. C. Cheung, S. Larson, J. D. Scargle, et al. *Fermi Large Area Telescope detection of gravitational lens delayed γ flares from blazar B0218+357*. *ApJ*, 782, L14, 2014.

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