Gamma-Gamma Absorption in γ-ray Binaries

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Abstract. Gamma-ray binaries are a class of high-mass binary systems, which are distinguished by having spectral energy distributions which peak above 1 MeV. Gamma-ray binaries consist of a compact object, either a neutron star or black hole, orbiting a massive O or B-type star. While there is some debate around how the gamma rays are produced, in two systems, PSR B1259-63 and PSR J2032+4127, the compact object is known to be a pulsar, and the gamma ray production is due to particle acceleration in the shock that forms between the pulsar and stellar winds. It has been suggested by some studies that there may be different sites of particle acceleration in these systems, with the GeV and TeV emission being produced in different locations. Gamma-gamma absorption of the TeV emission could significantly modify the observed emission. This may provide a mechanism to constrain the location of the production of TeV gamma rays. We plan to model the effect of gamma-gamma absorption in six of the seven known gamma-ray binary systems, in order to investigate how this will modify the observed spectrum. This may be used to place constraints on the production location when combined with the observations of the TeV emission. We will investigate this for the upcoming Cherenkov Telescope Array (CTA). We present the initial results from this project.

1. Introduction

Gamma-ray binaries are high-mass binary systems which consist of a compact object, either a neutron star or a black hole, in orbit around a massive O or B type star. Gamma-ray binaries are differentiated from X-ray binary systems by their spectral energy distributions (SED) which peak above 1 MeV. The recently discovered γ-ray binary LMC P3 is the first γ-ray binary discovered outside of our own galaxy, found in the Large Magellanic Cloud (LMC) [1]. To date there are only seven known γ-ray binary systems, the newest is PSR J2032+4127 [2]. Out of all of these systems, in only two, PSR B1259-63/LS 2883 and the newly discovered PSR J2032+4127, is the nature of the compact objects known to be pulsars [3, 4]. Although all of these systems consist of the same or similar components the nature of their orbital parameters can differ substantially. While the underlying emission mechanism is likely the same, differences in the orbital parameters, pulsar spin down luminosities, and the presence or absence of a discretion disc around the companion star, will modify the observed emission.

In the two aforementioned binary systems the most probable mechanism that produces γ-rays is the interaction between the stellar wind and the pulsar wind. However, the possibility of a microquasar scenario cannot be ruled out for the other systems. In this case γ-rays can be produced via Compton scattering close to the base of the relativistic jets.

There is still an open question of whether the GeV and TeV emission arises at the same location. Measuring the γ-γ absorption in γ-ray binaries can lead to a method of constraining the location of the GeV and TeV emission. The γ-γ absorption is dependent on the binary parameters, the stellar temperature and the viewing angle of the observer. In general, more absorption occurs when the compact object, or γ-ray emission region, is behind the companion star, which leads to a denser photon field for the γ-ray to travel through to reach an observer. The position of the γ-ray emission region is not necessarily located at the position of the pulsar but also at the shock front, which forms between the pulsar and the companion star.

2. Theory

A γ-ray photon with energy E_γ emitted at a certain location travelling in the direction e_γ will come into contact with a stellar photon with a certain energy ϵ travelling in the direction $e_\star$ after a certain path length l. If the energy of the stellar photon exceeds the threshold energy for γ-γ absorption (ϵ_{min}) then the γ-ray photon will undergo γ-γ absorption, or $e^- e^+$ pair-production, where both photons are eliminated and in the process an electron-positron pair will be produced.

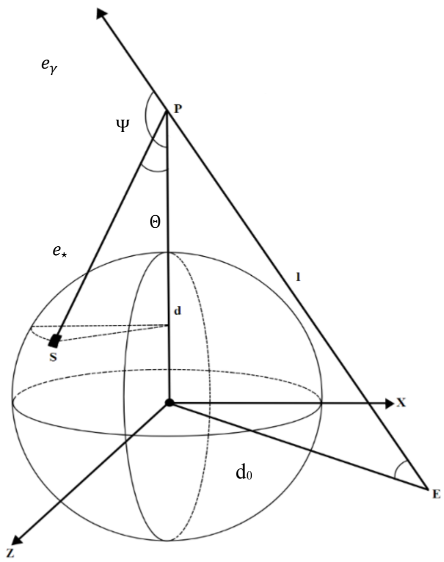

Figure 1. Geometry for γ-γ absorption due to $e^- e^+$ pair-production a Ψosition P between a γ-ray emitted at E and a stellar photon emitted at S. The γ-ray is emitted at an angle Ψ_0, relative to the stellar centre and the line PE, and travels a distance l towards an interaction point P. The distances d_0 and d describe the distances from the stellar centre towards the emission region and interaction position respectively. The vector motion of the stellar photon and γ-ray photon are described by $\overrightarrow{e_\star}$ and $\overrightarrow{e_\gamma}$ respectively.

The differential optical depth is given by [5]

$$d\tau_{\gamma\gamma} = \left(1 - \overrightarrow{e_\gamma} \cdot \overrightarrow{e_\star}\right) n_\epsilon \sigma_{\gamma\gamma} d\epsilon d\Omega dl, \tag{1}$$

where n_ϵ is the photon number density and $\sigma_{\gamma\gamma}$ is the γ-γ cross-section. If the companion star is assumed to be a perfect blackbody emitter, then the stellar photon number density is given by

$$n_\epsilon = \frac{2\epsilon^2}{h^3 c^3} \frac{1}{\exp(\epsilon/kT_\star) - 1} \text{ ph cm}^{-3} \text{ erg}^{-1} \text{ sr}^{-1}, \tag{2}$$

where ϵ is the photon energy, c the speed of light, h the Planck constant, k the Boltzmann constant, and $T_\star$ is the stellar surface temperature. The γ-γ cross-section is given by [6]

$$\sigma_{\gamma\gamma}(\beta) = \frac{3}{16}\sigma_{\rm T}(1-\beta^2)\left[(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\beta(2-\beta^2)\right], \tag{3}$$

where $\sigma_{\rm T}$ is the Thomson cross-section and β is given by

$$\beta = \sqrt{1 - \frac{2m_e^2c^4}{\epsilon E_\gamma(1-\overrightarrow{e_\gamma}\cdot\overrightarrow{e_\star})}}. \tag{4}$$

where m_e is the electron mass. In general, the opacity can be calculated using a quadruple integral which is dependent on l, θ, ϕ, and ϵ, and is given by

$$\tau_{\gamma\gamma} = \int_{l_{min}}^{l_{max}}\int_{\mu_{min}}^{1}\int_0^{2\pi}\int_{\epsilon_{min}}^{\epsilon_{max}} n_\epsilon\sigma_{\gamma\gamma}\left(1-\overrightarrow{e_\gamma}\cdot\overrightarrow{e_\star}\right)\,d\epsilon\,d\phi\,d\mu\,dl \tag{5}$$

where $\mu_{\rm min} = (1 - R_\star/d^2)^{1/2}$, $\mu = \cos\theta$, l is the path length the γ-ray travels, θ is the colatitude, ϕ is the longitude, and $\overrightarrow{e_\gamma}$ and $\overrightarrow{e_\star}$ are unit vectors depicting the directions of propagation of the gamma-ray photon and stellar photon respectively . In a point source approximation, the stellar photons are no longer emitted from various regions across the surface of a star but rather all of them are emitted from a single point located at the centre of the star. The γ-γ absorption in a point source approximation is [7]

$$\tau_{\gamma\gamma} = \int_{l_{min}}^{l_{max}}\int_{\epsilon_{min}}^{\epsilon_{max}} \pi\left(\frac{R_\star}{d}\right)^2 n_\epsilon\sigma_{\gamma\gamma}\left(1-\overrightarrow{e_\gamma}\cdot\overrightarrow{e_\star}\right)\,d\epsilon\,dl, \tag{6}$$

where d is the binary separation and $R_\star$ is the radius of the companion star. For each binary the opacity was calculated assuming the γ-rays are emitted at the centre of the compact object, except for PSR B1259-63 where the shock front location was also considered. The absorption at each orbital phase is calculated by determining the initial binary separation and interaction angle, and then integrating over the opacity function over the path length l and the photon energy ϵ.The point-source approximation is accurate to $\leq 2\%$ for the binary systems considered here.

3. Results

The results presented in this paper show the behavior of the γ-γ absorption for various orbital parameters and γ-ray photon energies. The binary parameters used for modelling the γ-ray binary systems are given in table 1. The binary separation of these systems has been calculated for both a neutron star and black hole compact object.

Table 1. Parameters used for modelling the γ-ray binary systems.

	HESS J0632+057[a]	**PSR B1259-63**[b]	**LS I+61°303**[c]	**1FGL J1018.6-5856**[d]	**LS 5039**[e]
$P_{\rm orb}$(days)	315(5)	1236.72432(2)	29.496(3)	16.544	3.90603(8)
e	0.83(8)	0.8698872(9)	0.54(3)	0.31±0.16	0.35(3)
ω (°)	129(17)	138.6659(1)	41(6)	89±30	226
i (°)	47&80	19&31	10&60	33&41	20&60
$T_\star$ (K)	30000	33500	22500	38900	39000
$R_\star$ ($R_\odot$)	8.0	9.2	10.0	10.1	9.3
$M_\star$ ($M_\odot$)	16.0	31.0	12.0	20.0&26.4	23.0
$M_{\rm compact}$ ($M_\odot$)	2.0&4.0	1.4	1.4&4.0	2.0	1.4&4.5
$\phi_{\rm periastron}$	0.967	0	0.23	0.974	0

[a] [8, 9, 10], [b] [11, 12, 13], [c] [14, 15, 16, 17, 18], [d] [19, 20, 21], [e] [22, 23, 24]

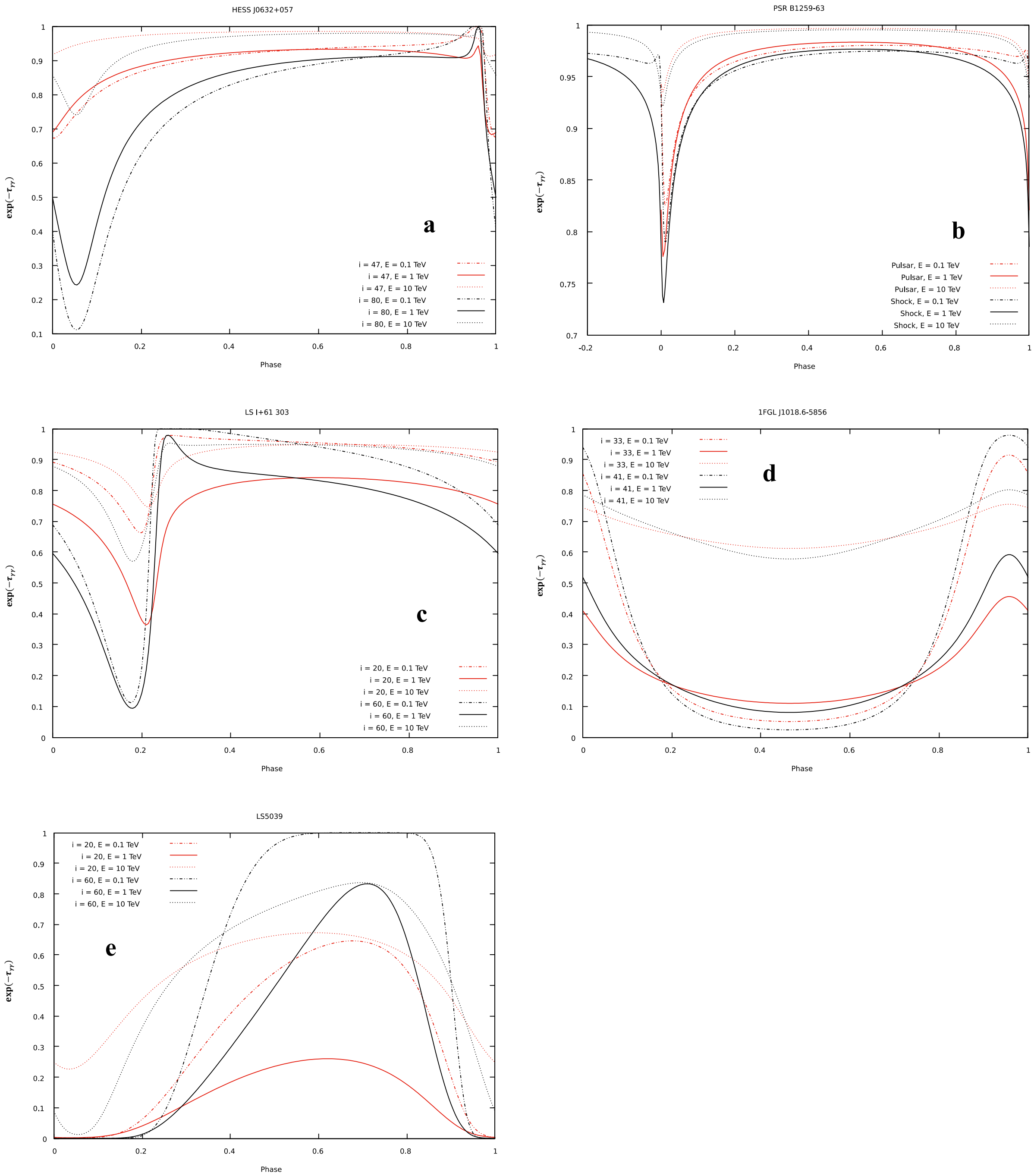

Figure 2. The γ-γ absorption HESS J0632+057 (a), PSR B1259-63 (b), LS I+61°303 (c), 1FGL J1018.6-5856 (d), LS5039 (e), plotted as $\exp(-\tau_{\gamma\gamma})$ vs. orbital phase. The lines denote the behaviour of the γ-γ absorption vs. phase for γ-ray energies of 0.1 TeV (dot-dashed line), 1 TeV (solid line), and 10 TeV (dotted line). The inclination for each system is given in the key with their respective line colours, where the red line represents the case where the compact object is a neutron star and the black line the case of a black hole. For PSR B1259-63/LS 2883 the red line represents the γ-γ absorption when the γ-ray emitting region is assumed to be at the pulsar location and the black line when it is assumed to be at the shock-front location.

For PSR B1259-63 the γ-γ absorption was calculated assuming two different locations of the γ-ray emission region, one being at the position of the pulsar and the other at the shock-front between the pulsar and the companion star. The distance between the pulsar and the apex of the shock-front can be estimated using [25]

$$r_{\mathrm{p}} = d\frac{\sqrt{\eta}}{(1+\sqrt{\eta})}, \tag{7}$$

where η is the ratio of the ram pressure of the stellar and pulsar wind which was set as $\eta = 0.05$. The resulting γ-γ absorption calculations are shown in figure 1. For the "neutron star or black hole" case, two different compact object masses were chosen where each has its own corresponding inclination angle. For 1FGL J1018.6-5856 the exact mass of the companion star is unknown but the compact object mass is believed to be approximately 2.0 $M_{\odot}$. Therefore the companion star mass was chosen to vary and the γ-γ absorption was calculated for a companion star mass of 20 $M_{\odot}$ and 26.4 $M_{\odot}$.

The results presented here for all systems show a similar trend where maximum absorption occurs close to superior conjunction. However, the magnitude of the absorption is most likely slightly underestimated by the point source approximation due to fact that it does not consider the effects of the angles described by θ and ϕ, which close to the companion star slightly underestimates the stellar photon density. However, the underestimation effect of the point source approximation at large distances becomes less (see Dubus 2006).

4. Discussion & Conclusion

In γ-ray binaries the maximum GeV and TeV emission should occur at or near superior conjunction because of the high angular dependence of inverse Compton scattering. However, at superior conjunction the energy of the very high energy (VHE) photons may exceed the energy threshold for γ-γ absorption which also leads to a maximum absorption of the TeV emission at superior conjunction. Hence, what may be observed, is that the maximum GeV emission occurs at or near superior conjunction and the maximum TeV emission occurs at or near inferior conjunction. This effect has been proposed for γ-ray binaries previously [6]. In particular, it has been suggested as a mechanism to explain the difference in the GeV and TeV light curves for LS 5039 and LMC P3 [6, 26, 27]. It has also been suggested as a mechanism to explain the local minimum seen in the TeV light curve of PSR B1259-63/LS 2883 [28]. For closely separated binaries the absorption period would occur throughout a much larger timeframe since the absorption is not only dependent on the angle of interaction but also on the separation distance and hence the energy density of the optical photons. For LS 5039 a relative amount of absorption will still occur even if the interaction angle is not optimal since the separation distance between the γ-ray emission region and the companion star is small. For highly eccentric binary systems such as PSR B1259-63/LS 2883 the absorption timeframe is very short and occurs only close to periastron. In future work we will now expand the modelling to investigate in what regions the TeV emission can and cannot originate from by means of absorption maps where regions around the binary system are also considered, and investigate how γ-γ absorption will modify the observed spectrum. This will be used to make predictions for future CTA observations.

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