The contribution of photons from the circumstellar disc to gamma-gamma absorption in PSR B1259-63

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Abstract. The gamma-ray binary system PSR B1259-63, consists of a Be star and a pulsar, and is one of only a few know high mass binary systems where the spectral energy distribution, in the νF_ν representation, peaks in the gamma-ray regime. It is also the only very high energy emitting gamma-ray binary where the nature of the compact object is known. Near periastron, the pulsar passes through the circumstellar disc that surrounds the Be star companion. Observations around periastron show a local minimum in the TeV gamma-ray flux, when the seed photon energy density, and hence the inverse Compton flux, should be highest. This discrepancy may be explained through gamma-gamma absorption. The contribution of the photons from the circumstellar disc surrounding the Be star significantly modifies the gamma-gamma absorption and may significantly modify the very high energy light curve.

1. Introduction

The binary system which consists of the pulsar PSR B1259-63 and the Be type star LS 2883, is part of a growing number of high-mass binaries which produce the peak of their non-thermal emission at gamma-ray energies. These sources are collectively referred to as gamma-ray binaries (see [1] for a review of these systems). PSR B1259-63 is a 48 ms pulsar in a ~ 3.4 year orbit around the Be companion star (LS 2883), which is surrounded by a circumstellar disc [2, 3, 4]. Of the known Very High Energy (VHE) emitting gamma-ray binaries, PSR B1259-63/LS 2883 is the only system where the nature of the compact object is identified as a pulsar via radio pulsations, while arguments in favour of both pulsars and blackholes have been put forward for the other systems (e.g. [5, 6]).

In PSR B1259-63/LS 2883 the non-thermal emission is believed to originate from particles accelerated in the shock that occurs between the pulsar and stellar wind (e.g. [7, 8]) and this emission has been detected from radio to gamma-rays (see e.g. [9, 10] and references therein). At the highest energies, the TeV gamma-rays detected by H.E.S.S. [11, 12] can be produced through inverse Compton scattering of seed photons from the optical star. However, the high energy density of optical photons also provides a high number of photons for gamma-gamma absorption, which may decrease the observed gamma-ray emission. Dubus [13] previously considered this effect for the then known gamma-ray binaries, including a comparison to H.E.S.S. observations of PSR B1259-63/LS 2883, where the author considered the effect of the optical photons originating from the star, and did not investigate whether the emission from the circumstellar

disc surrounding LS 2883 would have an important effect. The latter was briefly discussed in [14], where it was shown that the disc might significantly contribute to gamma-gamma absorption.

The spectra of Be stars are known to have an excess of emission at infrared (in comparison to B stars) due to free-free emission from the circumstellar disc (see [15] for a review of Be stars) and this is clearly detected from LS 2883 [16]. The circumstellar disc appears to always be present in this system as indicated by the strong Hα emission line which has been observed around periastron [9, 10, 17]. In this proceedings contribution we further investigate the influence the circumstellar disc will have on the gamma-gamma absorption.

2. Gamma-gamma absorption

Pair production of an electron-positron pair can occur in the scattering of two photons if the combined energy of the photons is high enough. A gamma ray with an energy ϵ_γ must interact with a photon with an energy ϵ which is greater than or equal to the threshold energy (i.e. $\epsilon \geq \epsilon_{\rm th}$) which is given by

$$\epsilon_{\rm th} = \frac{2}{\epsilon_\gamma(1-\mu)}, \tag{1}$$

where $\mu = \cos(\theta)$, θ is the angle of interaction, and the energies of the photons are normalized to the electron rest-mass energy ($m_{\rm e}c^2$), i.e. $\epsilon = h\nu/m_{\rm e}c^2$. The minimum threshold occurs for a head-on collision ($\mu = -1$), and for a 1 TeV gamma-ray photon this will require photons with a threshold frequency of,

$$\nu \approx 6.3 \times 10^{13} \left(\frac{h\nu_\gamma}{1\ {\rm TeV}}\right)^{-1}\ {\rm Hz} \tag{2}$$

which is within the mid-infrared regime.

The gamma-gamma optical depth can be calculated from

$$\tau_{\gamma\gamma} = \int_0^l \int_0^{4\pi} \int_{\frac{2}{\epsilon_\gamma(1-\mu)}}^{\infty} n_{\rm ph}(\epsilon,\Omega)\sigma_{\gamma\gamma}(\epsilon,\epsilon_\gamma,\mu)(1-\mu)\,{\rm d}\epsilon\,{\rm d}\Omega\,{\rm d}x, \tag{3}$$

where the photon number density $n_{\rm ph}(\epsilon,\Omega)$ is determined from the disc and star, and $\sigma_{\gamma\gamma}$ is the gamma-gamma cross-section. The cross-section is expressed as

$$\beta = \sqrt{1 - \frac{2}{\epsilon\epsilon_\gamma(1-\mu)}}, \tag{4}$$

as

$$\sigma_{\gamma\gamma}(\beta) = \frac{3}{16}\sigma_{\rm T}(1-\beta^2)\left[(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\beta(2-\beta^2)\right], \tag{5}$$

where $\sigma_{\rm T}$ is the Thomson cross-section.

3. Stellar and circumstellar disc photons

The photon number density in equation (3) is determined from the photons originating from the circumstellar stellar disc and star. Below we briefly outline how we determine this contribution.

3.1. Circumstellar disc

The circumstellar disc has been modelled under the assumption that the disc has a single temperature ($T_{\rm disc} = 19\,800$ K), a radius $R_{\rm disc} = 50R_\star$, a constant opening angle ($\theta_{\rm disc} = 1^\circ$), and the density of the disc decreases with distance, r, as

$$\rho = \rho_0 \left(\frac{r}{R_\star}\right)^{-n}, \tag{6}$$

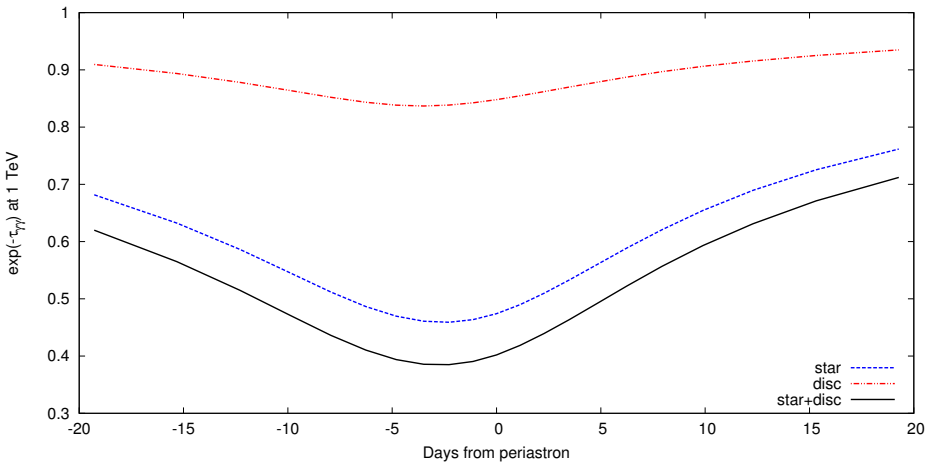

Figure 1. Extinction of a 1 TeV gamma ray due to gamma-gamma absorption resulting from photons that originate from the star (blue dashed line), the circumstellar disc (red double-dotted dashed line) and the combined effect (black solid line).

where $R_\star$ is the radius of the star and ρ_0 is the density of disc at the surface of the star [18]. The photon number density from the disc in every direction is calculate from

$$n_{\rm ph}(\nu) = \frac{mc}{h^2\nu} B_\nu \left(1 - {\rm e}^{-\tau_\nu}\right) \quad [{\rm cm}^{-3}\ {\rm ster}^{-1}], \tag{7}$$

where $B_\nu\left(T_{\rm disc}\right)$ is Planck's function and τ_ν is the optical depth through the disc. Following the method outlined in [18] the optical depth can be calculated from

$$\tau_\nu = \int X_\lambda X_\star R_\star^{-1} \left(\frac{r}{R_\star}\right)^{-2n} {\rm d}s \tag{8}$$

where X_λ is a wavelength dependent term which is a function of the disc temperature and the Gaunt factors (equation 5 in [18]) and the integration is along a line-of-sight through the disc. The remaining free parameters (n and $X_\star$) are found by fitting the free-free model to observational data and here we have used the same parameters as in [16].

3.2. Stellar photons

The stellar photons have been modelled assuming the star is a blackbody emitter with a temperature of $T_\star = 33\,000$ K. The attenuation of stellar photons due to absorption in the disc is calculated by decreasing the stellar component by $\exp(-\tau_\nu)$ if the line-of-sight passes through the disc.

4. Results

The gamma-gamma opacity around periastron for PSR B1259-63/LS 2883 has been calculated assuming that the gamma rays originate at a point source at the position of the pulsar. Here the binary parameters have been calculated assuming a mass of 1.4 $M_\odot$ for the pulsar, that LS 2883 has a mass of $M_\star = 31$ $M_\odot$ with a radius of $R_\star = 9.2$ $R_\odot$, the system has an orbital period of $P = 1236.7$ d and the eccentricity is $e = 0.87$. The extinction for a 1 TeV gamma-ray photon is shown in figure 1. As expected, the gamma-gamma absorption due to the disc is lower than that for the star but may still result in a decrease of more than 10 per cent at TeV energies. The combined contribution of both the stellar and disc photons results in an absorption of ≈ 60 per cent a few days before periastron.

5. Discussion & Conclusion

The light curve observed at TeV energies from PSR B1259-63/LS 2883 shows an apparent dip near periastron [12]. If the gamma rays are produced by inverse Compton scattering, it is expected that the emission should peak at periastron due to the increase in the seed photon density or remain constant around periastron in the case of saturation. This has lead to a number of possibilities, which have included the suggestions of hadronic models [19] which are, however, in contradiction to the inferred location of the circumstellar disc, and the introduction of variable adiabatic cooling around periastron [20, 21]. The gamma-gamma opacity was also investigated by [13] who showed an absorption of 40 percent of the VHE flux (above 380 GeV) near periastron for a stellar temperature of $T_\star \approx 27\,000$ K. However, the newer estimate for the stellar spectral type suggests a higher temperature ($T_\star \approx 33\,000$ K) [3]. This significantly increases the number of photons and increases the gamma-gamma opacity. The effect of the circumstellar disc was also not considered.

Here we have shown that the increase in the temperature of star, plus the addition of the circumstellar disc increases the gamma-ray absorption to a maximum of approximately 60 per cent near periastron for a 1 TeV photon. For gamma rays originating close to the pulsar this will result in a significant effect on the observed light curve. While this alone is not sufficient to explain all the details of the H.E.S.S. observations around periastron, we argue that gamma-gamma absorption will have a significant effect and must be included when attempting to model the VHE emission from this binary system, as well as others that include a Be companion.

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