Mem. S.A.It. Vol. 83, 246

Memorie della

Modeling the IC gamma-ray emission in the Be-pulsar binary PSR B1259-63

P. J. Meintjes and B. van Soelen

Department of Physics, University of the Free State, Po Box 339, Bloemfontein, 9300, South Africa: e-mail: [MeintjPJ;vansoelenb]@ufs.ac.za

Abstract. In this paper the possible gamma-ray production via anisotropic inverse Compton scattering has been investigated near periastron in the pulsar-Be binary PSR B1259-63. It has been shown that the Be-star, SS 2883, with its circumstellar disc (average photon energy $\langle\epsilon_{\rm ph}\rangle \sim 0.005$ eV) can provide a rich source of infrared photons, which can be upscattered to high energy gamma-rays with energies $\epsilon_\gamma \leq 2$ TeV by electrons with Lorentz factors $\gamma_{\rm e} \leq 10^7$, in the Thomson limit. The presence of a vast circumstellar disc, even after the recent periastron passage, has been inferred from recent spectroscopic observations. Utilizing an analytical expression for the anisotropic IC kernel, the inverse Compton scattering has been modeled, together with the possible gamma-ray absorption through photon-gamma collisions. It has been showed that the star-disc system provides a significant photon background resulting in a gamma-ray optical depth of $\tau_\gamma \sim 1000$ above $\epsilon_\gamma \sim 50\,$GeV, if we consider an impact factor similar to the pulsar–star separation at periastron.

Key words. radiation mechanisms: non-thermal – pulsars: individual: PSR B259-63 – X-rays: binaries

1. Introduction

The Be X-ray binary pulsar PSR B1259-63 consists of a 48 ms pulsar orbiting the Be star SS 2883 ($m_{\rm v} \sim 10$) in a highly eccentric orbit ($e \approx 0.87$), making a periastron passage every $P_{\rm orb} \approx 3.4$yr (Johnston et al. 1994). The system has been detected in TeV gamma-rays weeks before and after periastron passage during two previous campaigns (e.g. Aharonian et al. 2005, 2009). The circumstellar disc is believed to be mis-aligned with the orbital plane, with the pulsar passing through it twice during a single periastron passage (Aharonian et al. 2005). Based upon the dispersion and ultimate disappearance of the 48 ms radio pulse period (Johnston et al. 1999) before and after periastron, a disc size up to $50R_*$ is inferred (van Soelen & Meintjes 2011), where $R_* \sim 6R_\odot$ (Johnston et al. 1994). Since the circumstellar discs around Be-type stars contribute significantly toward the total soft photon spectrum of the Be-type star, especially in the infrared (IR), a significant circumstellar disc may provide a vast reservoir of soft photons, which may be upscattered to high energies by relativistic electrons through inverse-Compton (IC) scattering in the pulsar-wind shock front, close to disc crossing epochs. The scattering process will occur in the Thomson limit, where the cross section significantly exceeds the IC cross section in the Klein-Nishina limit. In a resent

Send offprint requests to: P.J. Meintjes study (van Soelen & Meintjes 2011), the possible IC gamma-ray emission close to periastron has been modeled using an isotropic approach. This study, although with limitations due to the isotropic assumption, pointed out that the ratio of IC scattering from the combined disc-star system, opposed to the star alone, is approximately 3. In this study the anisotropic IC scattering is going to be investigated, with an anisotropic IC kernel (Fargion, Konoplich & Salis 1997). The paper is structured as follows: In Section 2 the disc parameters and expected IR excess inferred through observations and modeling are presented. In Section 3 and Section 4, the IC scattering process, as well as some results related to the anisotropic modeling are presented respectively. In Section 5 the gamma-ray opacity of the Be-star system is discussed, with some conclusions presented in Section 6.

2. The circumstellar disc

Based upon the dispersion measurements of the radio pulse around periastron passage (Johnston et al. 1999) a disc size of $\sim 50\ R_*$ has been inferred in a recent study of the IC gamma-ray emission from PSR B1259-63 (van Soelen & Meintjes 2011). It has been shown that the IR data from 2MASS and MSX(A,C) can readily be fitted with a Curve of Growth (COG) method (Lamers & Waters 1984). The fit in Fig. 1 is based upon a disc opening angle of 5° and a disc temperature of $T_\mathrm{d} = 0.5T_* \sim 12500$ K (van Soelen & Meintjes 2011). The deduced photon spectrum, which will be utilized in the inverse Compton modeling, is presented in Fig. 2. A wide disc with inner temperature close to $T \sim 10000$ K, which is observed at a shallow inclination (i.e. not exactly face on) could provide an observable H_α signature. The velocity dispersion of the emission line could also provide a clue regarding the size and temperature profile of the circumstellar disc. Recent (April 2011) spectroscopic observations (Fig. 3) made with the South African Astronomical Society (SAAO) 1.9 m telescope, utilizing the Grating Spectrograph with a 1200 lines mm^{-1} grating and ~ 1 Å resolution, revealed a very prominent H_α line, suggesting a wide disc structure surrounding SS 2883. These observations show that 4 months after periastron a significant circumstellar disc still exists around SS 2883, contrary to expectation that the pulsar would have disrupted it severely during this, and previous, periastron passages. The expected thermal dispersion from a $T \sim 10^4$ K gas is approximately $\Delta v \sim 20\,\mathrm{km\,s^{-1}}$, opposed to the observed $\Delta v \sim 2000\,\mathrm{km\,s^{-1}}$ ($\Delta\lambda \approx 50$ Å). Also visible from the broad H_α line, is the absence of the stellar H_α absorption, indicating that the circumstellar disc contribution completely dominates the stellar absorption at the same fre-

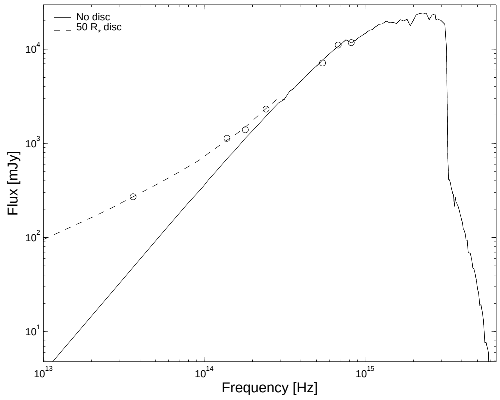

Fig. 1. A Kurucz stellar (Kurucz 1979) atmosphere (solid line) for the B-type star and the modification created by a 50 R_* circumstellar disc, obtained from a COG fit (dashed line) to optical and infrared data of SS 2883 (van Soelen & Meintjes 2011).

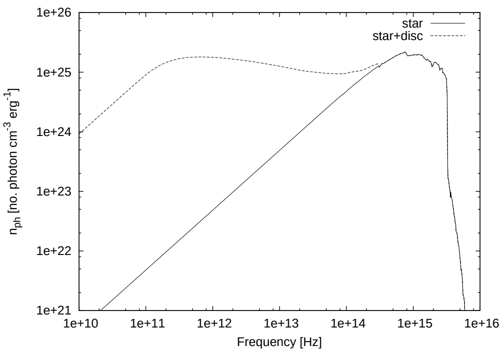

Fig. 2. The deduced star-disc photon spectrum based upon the COG fit through IR data of the blue Be-star (SS 2883) in PSR B1259-63.

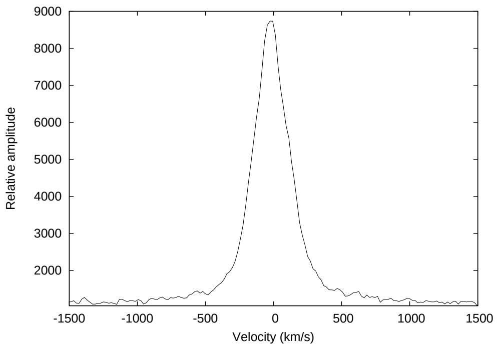

Fig. 3. The velocity dispersion of the observed H_α Balmer line observed recently (April 2011) using the Grating Spectrograph on the SAAO 1.9 m telescope at Sutherland.

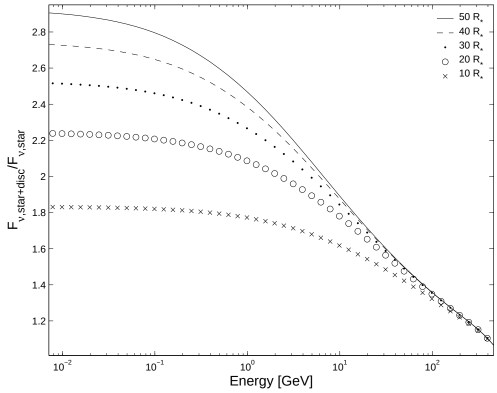

Fig. 4. The contribution of the disc size towards the total isotropic IC flux ratio $F_{\rm star-disc}/F_{\rm star}$.

quency. This may provide indirect justification of an unusually large circumstellar disc orbiting SS 2883.

3. IC scattering

The presence of a soft photon excess contributed by the circumstellar disc makes IC scattering in the Thomson limit an attractive mechanism for gamma-ray production in PSR B1259-63, especially when the pulsar crosses the circumstellar disc. For electron energies between $\gamma \sim 10^4 - 10^7$ (Kirk, Ball & Skjaeraasen 1999), one can show that photon energies $\epsilon_{\rm ph} \leq 50\,{\rm eV}$ ($\gamma \sim 10^4$) and $\epsilon_{\rm ph} \leq 0.05\,{\rm eV}$ ($\gamma \sim 10^7$) will produce gamma-rays in the Thomson limit. Assuming a standard blackbody spectrum the B2e star (SS 2883) will have a surface temperature of $T_* \sim 25\,000$ K, resulting in an average photon energy of $\langle \epsilon_{\rm ph} \rangle \sim 5$ eV, while the disc will contribute to the soft photon excess below this energy (e.g. see Fig. 2). This shows that both the stellar and disc photon populations will contribute together towards the IC scattering in the Thomson limit. In the Thomson limit it is possible to create gamma-rays of energies,

$$\epsilon_\gamma \leq 2\left(\frac{\gamma_{\rm e}}{10^4}\right)^2 \left(\frac{\epsilon_{\rm ph}}{5\,{\rm eV}}\right) {\rm GeV}$$

$$\epsilon_\gamma \leq 2\left(\frac{\gamma_{\rm e}}{10^7}\right)^2 \left(\frac{\epsilon_{\rm ph}}{0.005\,{\rm eV}}\right) {\rm TeV}$$

where $\epsilon_{\rm ph} \sim 5\,{\rm eV}$ and $\epsilon_{\rm ph} \sim 0.005\,{\rm eV}$ represent a star and disc photon respectively with energies significantly below the limiting energy for the Thomson limit scattering.

4. Anisotropic IC scattering

A first attempt to model the contribution of the circumstellar disc on the IC gamma-ray production utilized an isotropic IC scattering kernel (van Soelen & Meintjes 2011). This approach, although with limitations, pointed out that the combined disc-star system does contribute noticeably more towards the IC gamma-ray flux than the B-type star alone.

One can also see that the disc size does contribute towards the magnitude of the gamma-ray flux ratio (Fig. 4), for example a large disc of $50R_*$, results in a ratio of $F_{\rm star-disc}/F_{\rm star} \geq 2$.

Using an anisotropic IC kernel the total scattering rate per unit energy, in the Thomson limit (Fargion, Konoplich & Salis 1997) is

$$\frac{dN_{\rm Thom}}{d\epsilon_1 dt} = \frac{\pi c r_e^2}{2\beta_{\rm e}\gamma_{\rm e}^2\epsilon_{\rm ph}} \times [3 - C_{\theta,\circ}^2 + (3C_{\theta,\circ}^2 - 1) \times \frac{1}{\beta_{\rm e}^2}[\frac{\epsilon_1}{\gamma_{\rm e}^2\epsilon_{\rm ph}(1-\beta_{\rm e}\cos\theta_\circ)} - 1]^2],$$

where $C_{\theta,\circ} = \cos\theta'_\circ = \frac{\cos\theta_\circ - \beta}{1-\beta_{\rm e}\cos\theta_\circ}$. Here θ' represents the angle between the incoming photon and direction of the electron's momentum in the rest fame of the electron. The total scattering rate, with an arbitrary electron and photon spectrum is then

$$\frac{dN_{\rm tot}}{d\epsilon_1 dt} = \int\int\int \frac{dn_{\rm ph}}{4\pi d\epsilon_{\rm ph}} \times \frac{dN_{\rm Thom}}{d\epsilon_1 dt}\frac{dN_{\rm e,\gamma}}{d\gamma_{\rm e}} d\epsilon_{\rm ph} d\gamma_{\rm e} d\Omega_{\rm ph},$$

where $\frac{dn_{\rm ph}}{4\pi d\epsilon_{\rm ph}}$ represents the star-disc photon spectrum (i.e. Fig. 2), $\frac{dN_{\rm Thom}}{d\epsilon_1 dt}$ the Thomson limit anisotropic kernel, $\frac{dN_{\rm e}}{d\gamma_{\rm e}}$ the electron spectrum (usually a power law), and $d\Omega_{\rm ph}$ the geometry dependent solid angle of the star-disc system with respect to the pulsar at various positions along the orbit.

By adopting a geometry which considers a circumstellar disc which is perpendicular to the pulsar orbit, the IC scattering (arbitrary units), from the disc-star system has been determined at several positions along the orbit using the anisotropic kernel and the full Klein-Nishina cross-section. Fig. 5 shows the relative scattering rate from the star and disc, normallized to the peak of the star contribution, at periastron. The corresponding IC flux ratio $F_{\rm star-disc}/F_{\rm star}$ is shown in Fig. 6. The total integrated flux (arbitrary units) in the energy range $\sim$ 100 MeV - 100 GeV for the star-disc system and star has been determined, showing a culmination in the IC integrated flux slightly before periastron (Fig. 7).

5. Absorption effects

Although the disc contributes towards the total reservoir of soft photons that can be upscattered to γ-ray energies, the soft photon excess also contributes significantly towards gamma-ray absorption through gamma-photon interaction. It has been showed that the energy of a colliding gamma-ray and soft photon (in the lab. frame) which deposits enough energy in the Centre of Momentum (COM) frame for the creation of a stationary $e^{\pm}$ pair, satisfies the conservation principle $\epsilon_\gamma = 2m_{\rm e}^2 c^4/(\epsilon_{\rm ph}(1-\cos\theta))$. The cross-section

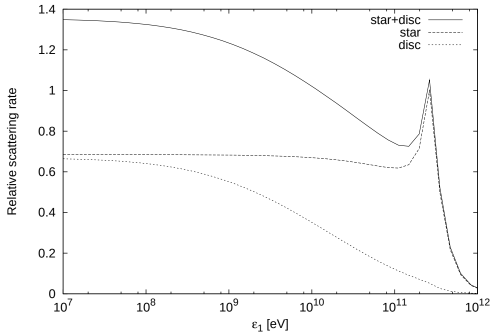

Fig. 5. The contribution of the star-disc system towards the total anisotropic IC scattering rate. The disc orientation is 90° with respect to the pulsar orbit, with the pulsar at periastron.

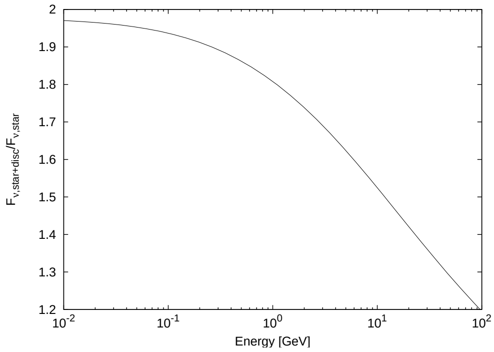

Fig. 6. The ratio of the anisotropic scattering rate of the star-disc system with respect to star alone, for a disc mis-aligned with 90°, with the pulsar at periastron.

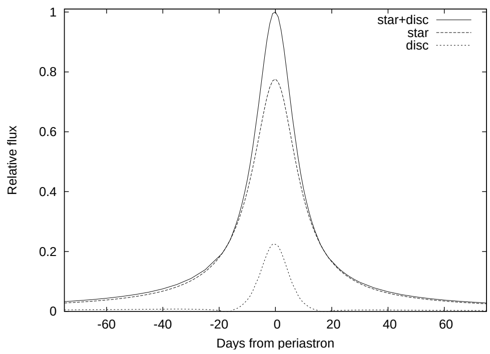

Fig. 7. The combined integrated anisotropic IC flux profile for a disc mis-aligned by 90° with respect to the pulsar orbit around periastron.

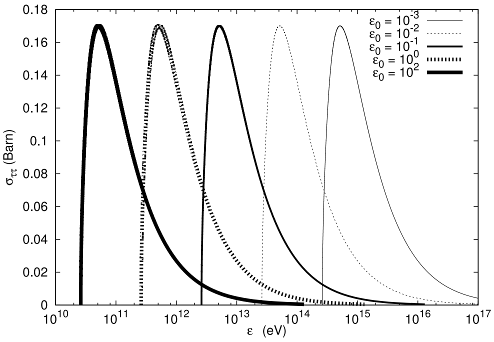

Fig. 8. The cross section ($\sigma_{\gamma\gamma}$) for head-on gamma-photon interaction in various relevant energy regimes.

for head-on ($\theta = 180°$) gamma-photon collisions are shown in Fig. 8, for photon energies between $10^{-3} - 10^{2}$ eV. The magnitude of the photon-gamma cross section $\sigma_{\gamma\gamma} \sim 0.2\sigma_{\rm Th}$, where $\sigma_{\rm Th}$ represents the Thomson cross section (Gould & Schréder 1967).

One can show that typical disc ($\epsilon_{\rm ph} \sim 0.005$ eV) and stellar photons ($\epsilon_{\rm ph} \sim 5$ eV) will absorb gamma-rays in the energy regimes

$$\epsilon_{\gamma} \geq 50\left(\frac{\epsilon_{\rm ph}}{5\,{\rm eV}}\right)^{-1} {\rm GeV},$$

$$\epsilon_{\gamma} \geq 60\left(\frac{\epsilon_{\rm ph}}{0.005\,{\rm eV}}\right)^{-1} {\rm TeV}.$$

The total optical depth for gamma-rays above 50 GeV is then

$$\tau_{\gamma\gamma} \sim \int \left(\frac{dn_{\rm ph}}{d\epsilon_{\rm ph}}\right)(1-\cos\theta)\sigma_{\gamma\gamma} d\epsilon_{\rm ph} dL,$$

which gives

$$\tau_{\gamma\gamma} \sim 10^{3}\left(\frac{n_{\rm ph}}{5\times10^{14}\,{\rm cm}^{-3}}\right)\left(\frac{L}{D_{\rm im}}\right).$$

Here $L = D_{\rm im}$ is the impact factor, i.e. the distance of closest approach, of the pulsar at periastron ($D_{\rm im} \sim 10^{13}$ cm). One can conclude that the system will be opaque to gamma-ray emission during periastron.

6. Conclusions

Here a qualitative investigation is launched of the possible contribution of the circumstellar disc towards the gamma-ray production through inverse Compton scattering. It has been shown that the disc contributes significantly to the soft photon population in the system, which will contribute noticeably to the total inverse Compton scattering rate of relativistic electrons in the pulsar wind shock, especially close to the disc crossings of the pulsar near periastron. It has also been shown that the disc-star system as a whole contribute twice as much to the IC scattering rate, compare to the B-type star alone. However, the huge reservoir of soft photons also contributes toward the gamma ray opacity through photon-gamma interactions. Gamma-rays above $\epsilon_{\gamma} \geq 50$ GeV will be severely affected, with the gamma-ray optical depth being as high a $\tau_{\gamma\gamma} \sim 1000$ over distance scales comparable to the distance of closest approach of the pulsar from the B-type star at periastron.

Acknowledgements. I am grateful to the organisers for the invitation to give a presentation at the 2011 Frascati workshop. The authors thank Alida Odendaal for the H_{α} spectrum of SS 2883. The authors are also grateful to Prof Okkie de Jager, who sadly passed away recently, for suggesting this project.

References

Aharonian, F., et al. 2005, A&A, 442, 1
Aharonian, F., et al. 2009, A&A, 507, 389
Fargion, D., Konoplich, R. V. & Salis, A. 1997, Z. Phys. C 74, 571
Gould, R. J. Schréder, G. P. 1967, Phys. Rev., 155, 1404
Johnston, S. et al. 1994, MNRAS, 268, 430
Johnston, S. et al. 1999, MNRAS, 302, 277
Kirk, J. G. Ball, L. Skjaeraasen, O. 1999, Astroparticle Phys., 10, 31
Kurucz, R. L. 1979, ApJS, 40, 1
Lamers, H. J. G. L. M. & Waters, L. B. F. M. 1984, A&A, 136, 37
van Soelen, B. & Meintjes, P.J. 2011, MNRAS, 412, 1721