Probing the Pulsar Wind in the γ-ray Binary System

– PSR B1259-63/SS 2883 –

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ABSTRACT

The spectral energy distribution from the X-ray to the very high energy regime ($>$ 100 GeV) has been investigated for the γ-ray binary system PSR B1259-63/SS2883 as a function of orbital phase within the framework of a simple model of a pulsar wind nebula. The emission model is based on the synchrotron radiation process for the X-ray regime and the inverse Compton scattering process boosting stellar photons from the Be star companion to the very high energy (100GeV-TeV) regime. With this model, the observed temporal behavior can, in principle, be used to probe the pulsar wind properties at the shock as a function of the orbital phase.

KEY WORDS: acceleration of particles- radiation mechanisms: non-thermal- gamma rays: theory -X-rays: binaries - pulsars: individual (PSR B1259-63)

1. Introduction

PSR B1259-63/SS 2883 system is composed of a Be star and a young pulsar with period $P = 47.76$ ms and a spin down energy of $\dot{E}_{sp} = 8\times10^{35}$ erg s^{-1}. The orbital properties of the γ-ray binary system associated with the Be star SS 2883 are unusual in that it has a large eccentricity ($e = 0.87$) and a wide orbit with period of 1287 days. This system had been known as a source of non-pulsed emission in the radio, X-ray and TeV energy bands. The origin of this high energy emission is likely related to the interaction of the pulsar wind of PSR B1259-63 with the outflow from the Be star (Tavani & Arons 1997). Their interaction results in the formation of a termination shock where the dynamical pressures of the pulsar wind and the stellar wind of the Be star are in balance. The shocked pulsar wind particles can emit non-thermal photons over a wide range of energies via the synchrotron radiation and inverse Compton processes.

In this paper, we fit the spectral properties of X-ray emissions with the pulsar wind parameters (Lorentz factor Γ_1 and magnetization σ) just before the shock. Within the framework of the interacting winds model, the observed temporal behavior of the flux and the photon index is caused by variations in the physical conditions at the termination shock of the pulsar wind. Because the distance of the shock from the pulsar is a function of the orbital phase, the physical properties of the pulsar wind can be probed as a function of the radial distance from the pulsar.

2. Theoretical model

The magnetization σ is defined by the ratio of the magnetic energy to kinetic energy in upstream of the shock. Using the magnetization σ and Lorentz factor Γ_1 of the pulsar wind, the particle number density and the magnetic field just before the shock is described as $n_1 = \dot{E}_{sp}/[4\pi\Gamma_1^2 r_s^2 m_e c^3(1+\sigma)]$ and $B_1 = \dot{E}_{sp}\sigma/[r_s^2 c(1+\sigma)]$, respectively, where r_s is the shock distance from the pulsar. We calculate the shock distance as a interaction between the pulsar wind the stellar wind from Be star.

For the post shock flow, the non-dimensional radial four velocity u_2, the proper number density n_2, the magnetic field B_2 and the gas pressure P_2 at the shock are derived using the jump conditions of a perpendicular MHD shock. For variation of the number density and the magnetic field as a function of the radial distance, we use the conservation of the number flux and the magnetic flux as $d(n(r)u(r)r^2)/dr = 0$ and $d(u(r)B(r)r/\Gamma_w)/dr = 0$, where Γ_w is the Lorentz factor of the post shock flow. Because the shock acceleration theories indicate a break in the particle energy distribution in the post-shocked flow around the injection energy, we assume that the downstream particles form a broken power law distribution described at $\Gamma = \Gamma_1$. In this paper, the spectral index

p_1 above $\Gamma > \Gamma_1$ is used as a fitting parameter. To compare the X-ray and γ-ray observations, we compute the synchrotron emissions of the shocked particles and the inverse-Compton process between the accelerated particles and stellar radiation from the Be star. We fit the observed X-ray properties with the magnetization σ, the Lorentz factor Γ_1 and the photon index p_1.

3. Resutls

In the present model, the observed temporal behavior is interpreted by variation in the wind parameters at the shock. An example of the fitting results are summarized in Table 1 and Figure 1, where the magnetization σ and the Lorentz factor Γ_1 are allowed to vary with orbital phase for a fix power law index. Table 1 represents variations of the fitting parameters, in which we refer to the orbital phases, where the X-ray data is available, as X1, X2, S1, A2, etc., following Chernyakova et al. (2006) and Uchiyama et al. (2009), and Figure 1 compares the model spectrum averaged during the 4-month time interval during the periastron passage with high-energy observations. X3 and A6 are corresponding to the phase near the apastron and $A5$ and $A2$ are near the periastron.

From Table 1 we find that the magnetization σ tends to increase as the pulsar approaches periastron (orbital phase A2), suggesting that the energy conversion process from the magnetic field to bulk motion of the pulsar wind varies on the scale of the shock distance in the binary. Also, we can see that fitting Lorentz factor Γ_1 is expected to vary about factor of 30 during one orbit. This large variation would imply that the observed emission in various orbital phases emanate from the different field lines (see Takata & Taam 2009 for more detail). As Figure 1 shows, the predicted level of the flux is consistent with the H.E.S.S. observations below 1 TeV (Aharonian et al. 2005), while the model predicts a softer spectrum than observed above 1 TeV. On the other hand, we find that detection by the Fermi telescope is not expected at the GeV energy bands for this model.

As alternative interpretation of the phase variation of the observed emissions, we fit the observations with σ and p_1 allowed to vary with the orbital phase for a given Lorentz factor Γ_1. Figure 2 represents the averaged spectrum during the periastron passage with the given Lorentz factor $\Gamma_1 = 5 \times 10^5$. In such a model. the emission from the shocked particles in the GeV band is expected to be detected by the *Fermi* telescope, as Figure 2 shows.

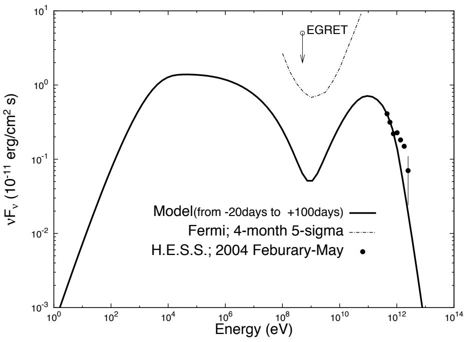

Fig. 1. The averaged spectrum of the emission from the shocked wind during the 4 month time interval from -20 days and +100 days (after Takata & Taam 2009). The spectrum is calculated with the model in which $p_1 = 3$ is fixed, and σ and Γ_1 vary with the orbital phase. The dashed-line represents the sensitivity for a 4-month observation using the $Fermi$. The filled circle is results of the observation done by H.E.S.S. (Aharonian et al. 2005).

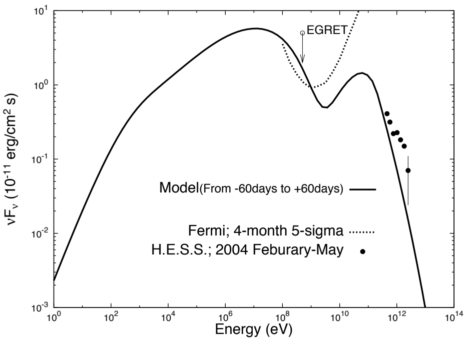

Fig. 2. The averaged spectrum of the emission from the shocked wind during a 4 month time interval from -20 days and +100 days and -60 days to +60 days (after Takata & Taam 2009). The spectrum is calculated with the model in which $\Gamma_1 = 5 \times 10^5$ is fixed, and σ and p_1 vary with the orbital phase.

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Orbital phase		X3	X6	X7	S1	S4	A5	A2	S6	A3	X1	X2	A6
Fitting parameters	σ ($\times 10^{-3}$)	0.8	1.2	2.2	2.1	11	11 & 15	6.2	70	9.2	3.3	1.7	
($p_1 = 3$)	$\Gamma_1(\times 10^6)$	8.5	7.6	7.8	1.1	1.7	0.57	0.3	1	0.8	2.8	8	6.5

Table 1. The fitted σ parameter and the Lorentz factor Γ_1. The results are for a power law index $p_1 = 3$