X-Ray and Gamma-Ray Emission from the PSR 1259-63/Be Star System

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Abstract

PSR 1259-63 is a radio pulsar orbiting a Be star in a highly eccentric orbit. Soft and hard X-rays are observed from this unique system. We apply the shock powered emission model to this system. The collision of the pulsar and Be star winds forms a shock, which accelerates electrons and positrons to the relativistic energies. We derive the energy distribution of relativistic electrons and positrons as a function of the distance from the shock in the pulsar nebula. We calculate the X-rays and γ-rays emitted from the relativistic electrons and positrons in the nebula at various orbital phases, taking into account the Klein-Nishina effect fully. The shock powered emission model can explain the observed X-ray properties approximately. We obtain from the comparison with observations that a fraction of ~ 0.1 of the pulsar spin-down luminosity should be transformed into the final energy of relativistic electrons and positrons. We find that the magnetization parameter of the pulsar wind, the ratio of the Poynting flux to the kinetic energy flux, is ~ 0.1 and may decrease with distance from the pulsar. We predict the flux of 10 MeV$-$100 GeV γ-rays which may be nearly equal to the detection threshold in the future projects.

1. Introduction

PSR 1259-63 is a 48 ms radio pulsar orbiting a Be star in a 3.4 yr orbit with eccentricity of 0.86 (Johnston et al. 1992a; Manchester et al 1995). The binary companion is a 10th magnitude B2e star SS 2883, whose mass and radius are estimated to be $\sim 10\ M_\odot$ and $\sim 6-10\ R_\odot$, respectively (Johnston et al. 1992b).

The X-rays have been detected from the PSR 1259-63 / SS 2883 system (see Hirayama et al. 1999 for references). The X-ray spectra are well represented by a power law function. The pulsation is absent in the X-ray intensity. Only upper limits are reported for the high energy γ-ray emission in the MeV$-$TeV γ-ray band (Tavani et al. 1996; Kawachi et al. 2002).

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The shock powered emission model for the high energy emission from the PSR 1259-63 / SS 2883 system has been developed by Tavani & Arons (1997) and Kirk, Ball & Skjaeraasen (1999). Adopting the shock powered emission model, we calculate the X-rays and γ-rays emitted from the shock accelerated particles at various orbital phases.

2. Nebula Emission

The pulsar wind collides with the stellar wind ejected from the Be star, forming a shock. We express the shock distance from the pulsar by a fraction (ξ) of the orbital separation a. The shock accelerates the pulsar wind particles, electrons and positrons, to the relativistic high energies (Hoshino et al. 1992). We assume that the accelerated relativistic electrons and positrons, which have the power law distribution with an exponent of p, are injected at the shock. The energy distribution of non-thermal relativistic electrons and positrons varies as they flow away from the shock, following a streamline, because of the radiative energy loss. The relativistic electrons and positrons in the nebula radiate keV $-$ MeV photons through the synchrotron emission and GeV $-$ TeV photons through the inverse Compton scattering of the photons from the Be star. An emission nebula, which radiates X-rays and γ-rays, extends in the shock down stream. Here, for simplicity, we approximate the nebula geometry by a cylinder.

We solve the integro-differential equation to obtain the particle distribution along a streamline (Blumenthal 1970). Then, we calculate the spectrum of X-rays and γ-rays radiated from the whole nebula, taking fully into account the particle distribution, the Klein-Nishina effect, the Planck distribution for the target photons of the inverse Compton scattering and the spectral function for synchrotron emission. We illustrate the X-ray and γ-ray spectra expected at periastron and apastron in Figure 1. Here the magnetization parameter of the pulsar wind, defined by the ratio of the Poynting flux to the kinetic energy flux, is taken as $\sigma = 0.1$, while the shock position parameter as $\xi = 0.1$. The parameters for the input particle distribution are chosen as $p = 2.1$, $\gamma_1 = 8 \times 10^4$, and $\gamma_2 = 3 \times 10^7$, where γ_1 and γ_2 are the minimum and maximum Lorentz factors, respectively.

The spectral shape in the X-ray band is well represented by a power law function with exponents of ~ 1 and ~ 0.7 at periastron and apastron, respectively. The steeper gradient at periastron is a direct consequence of a steeper particle distribution at periastron, caused by the efficient synchrotron cooling. The X-ray luminosity decreases slightly with the binary separation. If we adopt the larger values for the maximum Lorentz factor γ_2, the spectrum of the synchrotron

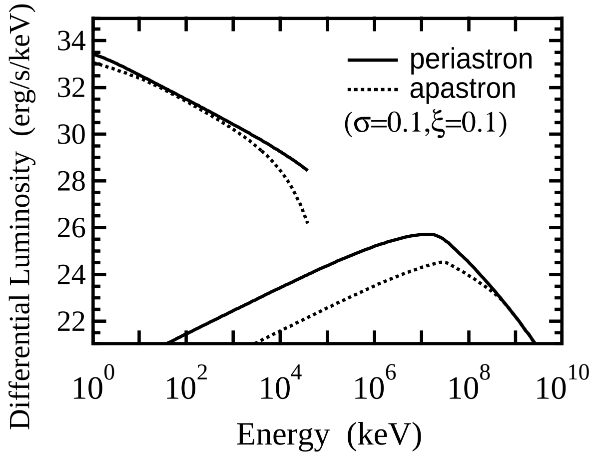

Fig. 1. Spectra of nebula emission at periastron (solid line) and apastron (dotted line).

component extends to higher energies. Hence, if the sensitivity of observations in the 10 MeV$-$1 GeV band is improved in future, the maximum Lorentz factor γ_2 of the particle acceleration would be determined.

The inverse Compton component peaks at a γ-ray energy of $\sim 10^{10}$ eV. The peak height of the inverse Compton component falls significantly with the binary separation because the density of target photons decreases and hence the inverse Compton scattering becomes less frequent as the binary separation enlarges. If the magnetic field at the shock is weak and the inverse Compton cooling dominates the synchrotron cooling, a larger number of relativistic electrons and positrons is required to produce such X-ray luminosity as shown in Figure 1. Then, the GeV$-$TeV γ-ray luminosity is enhanced considerably compared to that in Figure 1 (Kirk et al. 1999).

The adiabatic loss, though not included in calculations, may yield only the slight change on the spectral curve in Figure 1 and may not alter the essence of our results.

3. Comparison with Observations

The soft and hard X-rays observed from the PSR B1259-63/SS 2883 system have the following characteristics (Hirayama et al. 1999) : (1) the X-ray spectra are represented by a power law function that extends from 1 to 200 keV; (2) the spectral index varies with orbital phase, from ~ 2 at periastron to ~ 1.6 at apastron; (3) the X-ray luminosity in the $1-10$ keV band varies with orbital phase by about an order of magnitude, from $\sim 10^{34}$ ergs $\cdot$ s^{-1} near periastron to

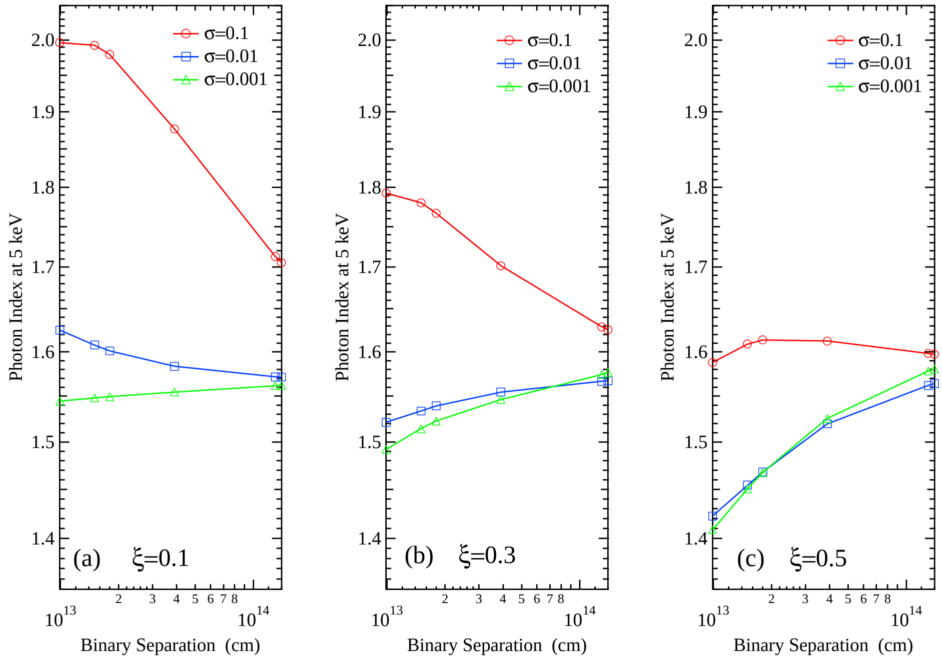

Fig. 2. Photon spectral indices calculated at 5 keV for various model parameters as a function of the binary separation.

$\sim 10^{33}\mathrm{ergs \cdot s^{-1}}$ at apastron, while just at periastron the light curve displays a drop by a factor of two compared to that slightly before or after the periastron; (4) the pulsation is absent in the X-ray time series.

We plot the photon spectral gradient (index) calculated at 5 keV for various model parameters as a function of the binary separation in Figure 2. The shock positions in Figures 2b and 2c are taken to be 3 and 5 times farther away from the pulsar, respectively, compared to that in Figure 2a. The magnetic field strengths at the shock are larger for larger σ and smaller a and ξ, while the target photon densities are larger for larger ξ and smaller a. We assume that the distributions of accelerated particles at the shock are the same irrespective of the binary phase. We fix the minimum and maximum Lorentz factors for the input particle distribution to $\gamma_1 \sim 8 \times 10^4$ and $\gamma_2 \sim 3 \times 10^7$, respectively. The change of the particle distribution in the nebula due to the radiative cooling is not significant at apastron. Hence, the photon spectral index at apastron reflects the original slope of the accelerated particle distribution. We adopt $p \sim 2.1$ determined from the photon index of ~ 1.6 observed at apastron. The observed photon index variation with orbital phase is approximately reproduced by the case with $\sigma \sim 0.1$ and $\xi \sim 0.1$ in Figure 2a.

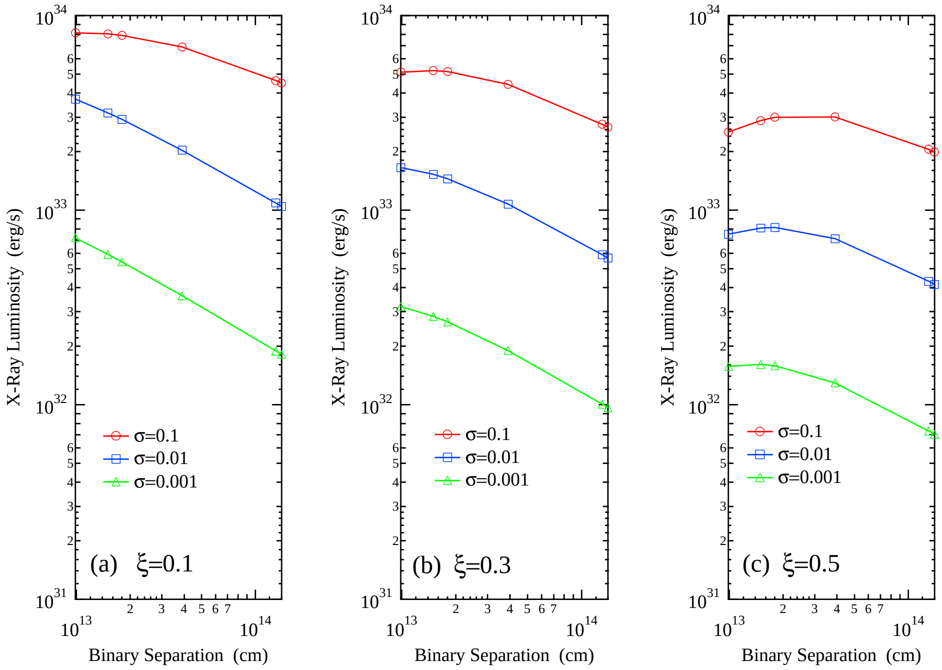

Fig. 3. Luminosity of X-rays in the $1-10$ keV band calculated for various model parameters as a function of the orbital separation.

We depict the X-ray luminosity in the $1-10$ keV band calculated for various model parameters as a function of the binary separation in Figure 3. The case with $\sigma \sim 0.1$ and $\xi \sim 0.1$ is again preferred from the relatively large observed X-ray luminosity. However, if the model parameters σ and ξ are taken to be constant throughout the binary orbit, the luminosity variation with orbital separation predicted by the model is too small to explain the observed variation amounting to an order of magnitude. This result suggests that the magnetization parameter σ may decrease with orbital separation while the shock position parameter ξ may increase with orbital separation.

Our results shown in Figure 1 are consistent with the COMPTEL and EGRET upper limits in the $1-1000$ MeV range (Tavani et al. 1996). Recently, the CANGAROO collaboration reports the new upper limit on the emission in the TeV range (Kawachi et al. 2002), which is well above our prediction and consistent with our results.

4. Concluding Remarks

The shock powered emission model considered here explains the observed X-ray and γ-ray properties approximately. We should note, however, that the reproduction of a luminosity drop in X-rays, observed just at periastron, is beyond the scope of our simple model. We need to construct the detailed model that includes the flow patterns of the Be star and pulsar winds, the misalignment of the pulsar orbital plane with the Be star outflow disk, the shielding of the emission region from the target photons for the inverse Compton scattering and the adiabatic loss in addition to the variation of model parameters σ and ξ with orbital separation.

The PSR 1259 - 63 / Be star binary is an unique system which can provide important information on the pulsar wind and the shock acceleration. Further observational and theoretical studies are encouraged.

References

1. Blumenthal G. R. 1970, Rev. Mod. Phys. 42, 237
2. Hirayama M. et al. 1999, ApJ, 521, 718
3. Hoshino M., Arons J., Gallant Y. A., Langdon A. B. 1992, ApJ 390, 454
4. Johnston S. et al. 1992a, MNRAS 255, 401
5. Johnston S. et al. 1992b, ApJ 387, L37
6. Kawachi et al. 2002, preprint
7. Kirk J. G., Ball L., Skjaeraasen O. 1999, Astroparticle Physics 10, 31
8. Manchester R. N. et al. 1995, ApJ 445, L137
9. Tavani M. et al. 1996, A&AS 120,221
10. Tavani M., Arons J. 1997, ApJ 477, 439