

Mechanism of the X-ray and Soft Gamma-ray Emissions from the High Magnetic Field Pulsar: PSR B1509-58

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We use the outer gap model to explain the spectrum and the energy dependent light curves of the X-ray and soft γ -ray radiations of the spin-down powered pulsar PSR B1509-58. In the outer gap model, most pairs inside the gap are created around the null charge surface and the gap's electric field separates the opposite charges to move in opposite directions. Consequently, the region from the null charge surface to the light cylinder is dominated by the outflow current and that from the null charge surface to the star is dominated by the inflow current. We suggest that the viewing angle of PSR B1509-58 only receives the inflow radiation. The incoming curvature photons are converted to pairs by the strong magnetic field of the star. The X-rays and soft γ -rays of PSR B1509-58 result from the synchrotron radiation of these pairs. The magnetic pair creation requires a large pitch angle, which makes the pulse profile of the synchrotron radiation distinct from that of the curvature radiation. We carefully trace the pulse profiles of the synchrotron radiation with different pitch angles. We find that the differences between the light curves of different energy bands are due to the different pitch angles of the secondary pairs, and the second peak appearing at $E > 10$ MeV comes from the region near the star, where the stronger magnetic field allows the pair creation to happen with a smaller pitch angle.

Keywords: pulsars, gamma-rays

1. INTRODUCTION

PSR B1509-58 (hereafter PSR B1509) is a young (about 1600 years old) spin-down powered pulsar with a period of about 150 ms and a surface magnetic field of $\sim 1.5 \times 10^{13}$ G, which is much stronger than those of most of the canonical pulsars ($\sim 10^{12}$ G). Multi-wavelength observations show that, from 0.1 keV to 10 MeV, PSR B1509 has a wide single peak (Matz et al. 1994, Kuiper et al. 1999, Cusumano et al. 2001 e.g.), when $E > 10$ MeV, another peak shows up near the peak of radio emission (Kuiper et al. 1999, Pilia et al. 2010, Abdo et al. 2010). PSR B1509 is unique for its softest γ -ray spectrum and a very strong surface magnetic field among the known γ -ray spin-down powered pulsars.

Here we give explanations for the spectrum and the energy dependent light curves of the X-ray and soft γ -ray radiations of the spin-down powered pulsar PSR B1509, based on the outer gap model. Cheng et al. (2000) showed that most electron/

positron pairs created inside the outer gap are produced near the null charge surface, the strong electric field inside the gap separates the opposite charges to move in opposite directions. Therefore from the null charge surface to the light cylinder the radiation is mainly outward, and from the null charge surface to the star the radiation is mainly inward. Since the light cylinder of PSR B1509 is much bigger than that of the Crab pulsar, most outflow curvature photons can escape from photon-photon pair creation. If the line of sight is in the direction of outgoing radiation beam, the spectrum of PSR B1509 should be a characteristic pulsar spectrum, namely a power law with exponential cut-off spectrum as predicted by Wang et al. (2010). Obviously this conflicts with the observation. Therefore, we propose that the viewing angle of PSR B1509 is in the direction of incoming radiation beam, where the hundreds MeV curvature photons are converted into pairs by the strong magnetic field. The observed X-rays and soft γ -rays are synchrotron radiation of these pairs.

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2. SIMULATION

We trace the field lines in the gap from the stellar surface to the light cylinder. At each step \vec{r} in the field line, we calculate the Lorentz factor of the particle, the pulse phase Ψ and the viewing angle ζ of the curvature radiation. Then we trace the direction of each incoming curvature radiation to find the place where the magnetic pair creation happens. The synchrotron radiation of the pair is a hollow cone, where the (Ψ, ζ) of each direction is calculated.

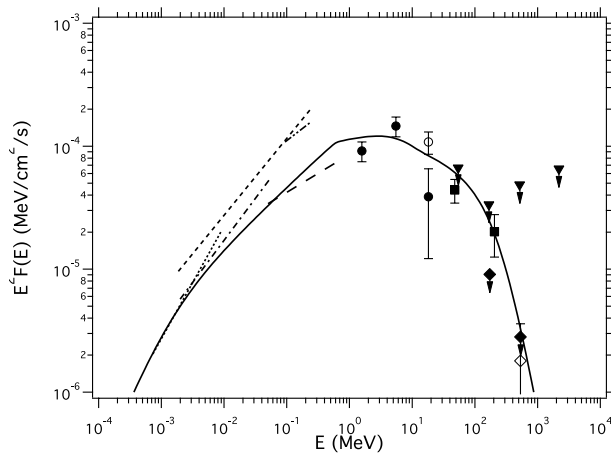
If the radiation satisfies $|\Psi - \beta| < 0.5^\circ$ where β is our viewing angle, we calculate its spectrum. Because some synchrotron photons approach the star and become pairs, we trace each direction of the synchrotron radiation to calculate the attenuation caused by the absorption of the magnetic field. The simulated phase averaged spectrum is the sum of the visible survival synchrotron radiation, which is shown in Fig. 1. The energy dependent light curves are obtained by integrating the phase resolved spectra. The number of the photons with $E_1 \leq E \leq E_2$ measured at pulse phases between Ψ_1 and Ψ_2 is calculated by

$$N_\gamma(E_1, E_2, \Psi_1, \Psi_2) \propto \int_{E_1}^{E_2} F_{tot}(E, \Psi_1 \leq \Psi \leq \Psi_2) dE. \quad (1)$$

Fig. 1 shows the simulated energy dependent light curve. The comparisons between the simulated light curves and the observed ones are given by Fig. 2.

3. DISCUSSION

- Where are the GeV curvature photons?



The magnetosphere of PSR B1509 can generate GeV γ -ray photons by accelerating the charged particles in the outer gap, as well as other γ -ray spin-down powered pulsars. However, these outgoing curvature photons are missed by our line of sight.

- Why is the cut-off energy of the spectrum so low?

This is due to the absorption of the magnetic field. The magnetic field of PSR B1509 converts not only the curvature photons emitted by the incoming particles to pairs, but also part of the synchrotron photons emitted by these pairs.

- Why is there a second peak at phase ~ 0 ?

The second peak of PSR B1509 is the synchrotron radiation emitted by the pairs with smaller pitch angles, which are converted from the curvature photons with higher energy emitted from the region of $20R_s < r < 30R_s$. For a fixed birth place, the curvature photons with higher E_{cur} become pairs earlier. These photons with higher energy can become pairs under smaller pitch angle θ_p , and the pairs are generated further from the star. If a synchrotron photon is emitted further from the star, it has higher chance to survive from the absorption of the magnetic field. When $\beta < \alpha$, the pulse phase of the synchrotron radiation is closer to 0 when the pitch angle is smaller, and closer to 0.5 when the pitch angle is larger.

- Why does the second peak show up when energy increases?

If the particle is made via the magnetic pair creation,

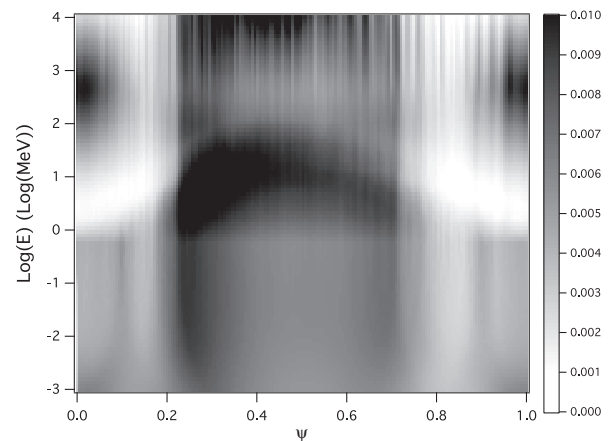


Fig. 1. *Left:* The simulated phase averaged spectrum of PSR B1509, comparing with the observed data provided by EGERT (triangles), COMPTEL (circles, Kuiper et al. 1999), AGILE (filled squares, Pilia et al. 2010), Fermi (diamonds, Abdo et al. 2010), ASCA (dot line, Saito et al. 1997), Ginga (dot-dashed line, Kawai et al. 1992), OSSE (long-dashed line, Matz et al. 1994), Wexler (dot-dot-dashed line, Gunji et al. 1994), and RXTE (short-dashed line, Marsden et al. 1997). *Right:* The simulated energy dependent light curves in the pulse phase and energy plane. The darkness represents the percentage of the number of the photons of certain pulse phase interval, in the total number of photons of certain energy range.

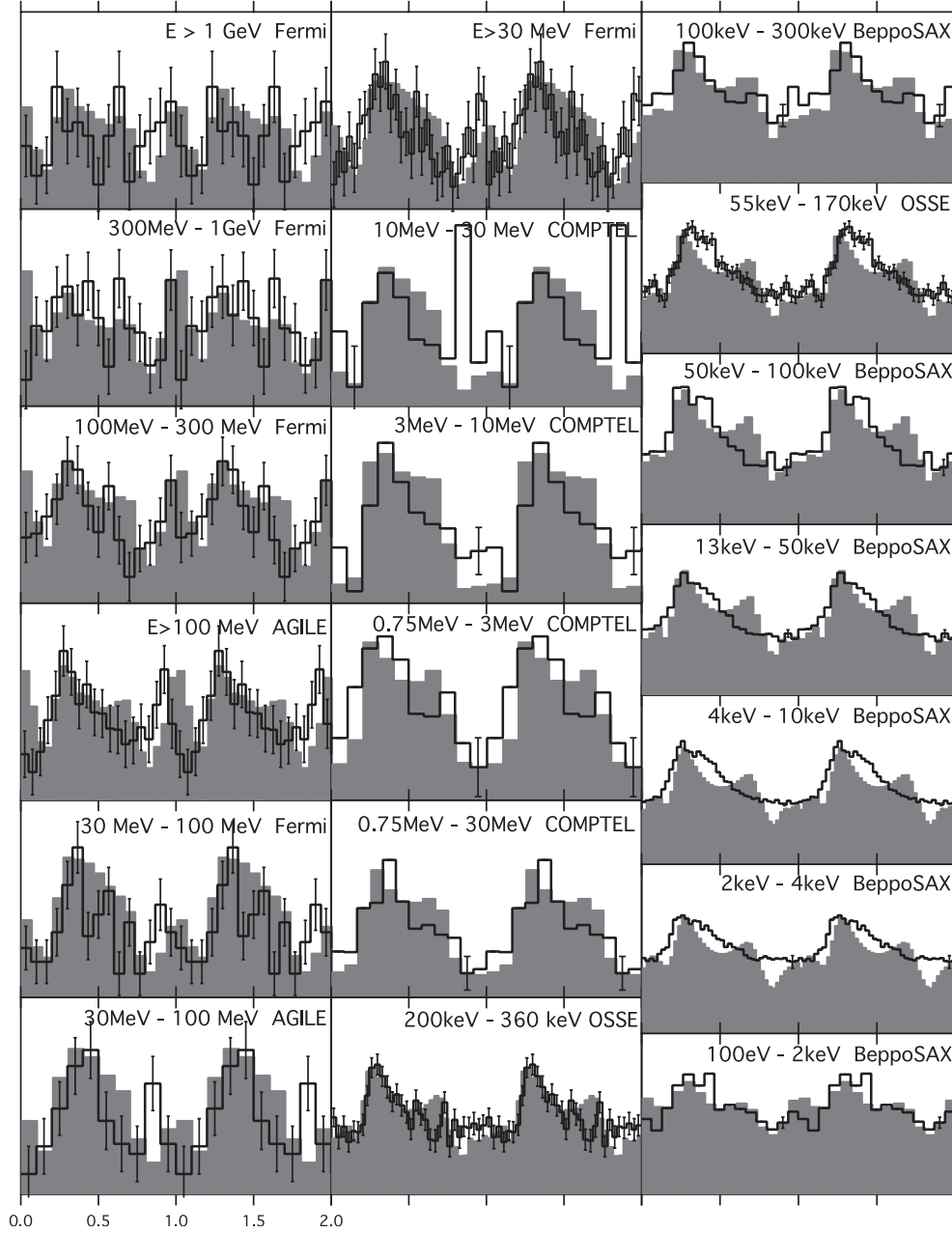


Fig. 2. The simulated energy dependent light curves (grey histograms), comparing with the observed data (solid lines), which are provided by Fermi (Abdo et al. 2010), AGILE (Pilia et al. 2010), COMPTEL (Kuiper et al. 1999), OSSE (Matz et al. 1994) and BeppoSAX (Cusumano et al. 2001).

the typical energy of its synchrotron radiation is proportional to the energy of its original curvature photon. The curvature photon with higher energy can become pair under smaller pitch angle, which leads to a pulse to phase close to 0. Therefore, for the same birth place of the curvature photons, if the viewing angle is smaller than the inclination angle, the observed spectrum of the synchrotron radiation, whose pulse phase is closer to 0, has higher cut-off energy.

4. CONCLUSION

The line of sight of PSR B1509-58 is in the direction of incoming beam instead of outgoing beam, otherwise a characteristic power law with exponential cut-off spectrum with cut-off energy around a few GeV should be observed. In order to avoid seeing the outgoing flux and fit the observed multi-wavelength light curves we need to choose inclination angle = 20° and viewing angle = 11° . The observed spectrum

is the synchrotron radiation emitted by the pairs produced by the magnetic field that converts the major part of the incoming curvature photons. We find that the differences between the light curves of different energy bands are due to the different pitch angles of the secondary pairs, and the second peak appearing at $E > 10$ MeV comes from the region near the star, where the stronger magnetic field allows the pair creation to happen with a smaller pitch angle.

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