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

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Abstract: We use the outer gap model to explain the spectrum and the energy dependent light curves of the X-ray and soft gamma-ray radiations of the spin-down powered pulsar: PSR B1509-58.

Introduction:

The outer gap model predicts that most pairs created inside the gap are around the null charge surface, and the electric field separates the opposite charges to move in opposite directions (Cheng, Ho & Ruderman, 1986). Consequently, from the null charge surface to the light cylinder the outflow radiation is dominant, whereas from the null charge surface to the star the inflow radiation is dominant. Since the electric field decreases rapidly from the null charge surface to the star, the incoming radiation flux is weaker than that of the outgoing flux. Furthermore most of the incoming high energy curvature photons are converted to pairs by the strong magnetic field of the canonical pulsars. Based on these model features we propose a model to calculate the non-thermal X-rays and soft gamma-rays emitted by the secondary pairs produced by converting the incoming curvature photons emitted by the primary charged particles.

Method:

Trace the field lines → Calculate the direction of the curvature radiation, $\vec{v}_{cur}$, at each step $\vec{r}$ → Trace $\vec{v}_{cur}$ of the incoming curvature radiation to find the place, $\vec{r}'$, where the pair creation happens

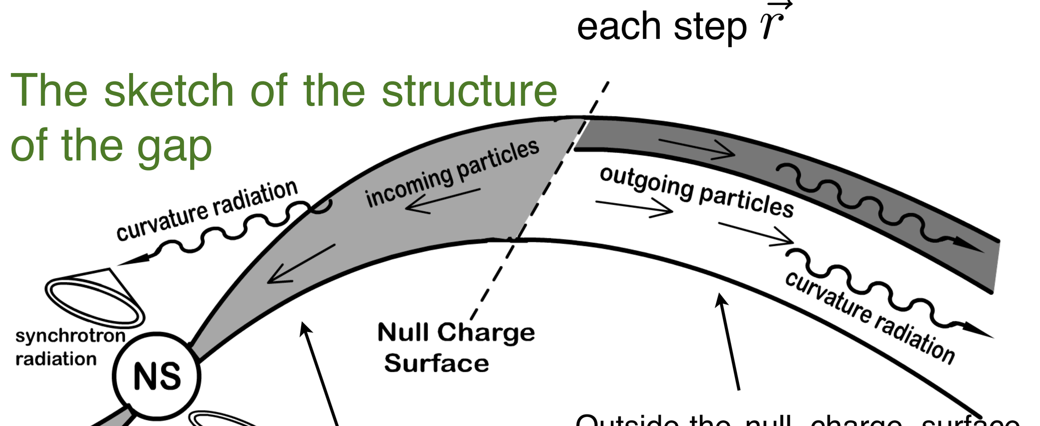
↓ Calculate the pulse phases and viewing angles, (ψ, ζ), of the hollow cone at $\vec{r}'$

↓ Calculate the spectrum of the radiation that satisfies $|\zeta - \beta| < 0.5°$, where β is the viewing angle

↓ Trace the direction of synchrotron radiation to calculate the attenuation of the radiation caused by the pair creation, and remove the photons that covered by the star

← Integrate the phase resolved spectra to obtain the energy dependent light curves

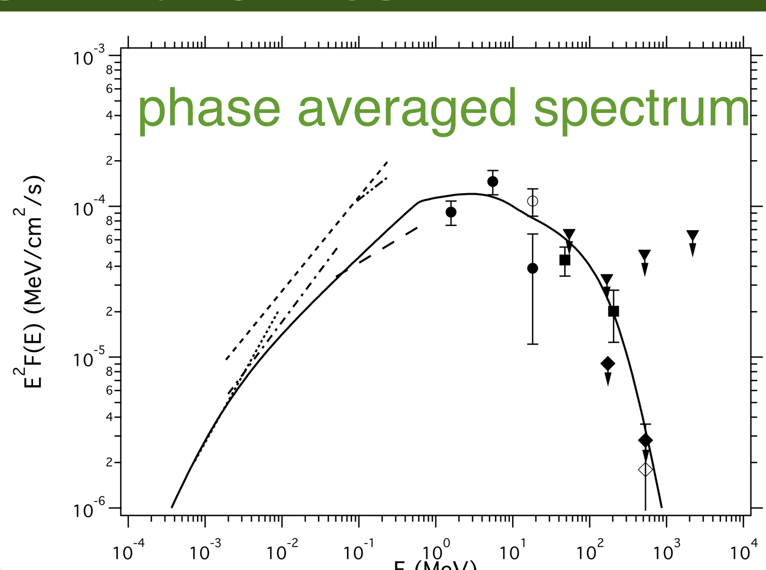
The sketch of the structure of the gap



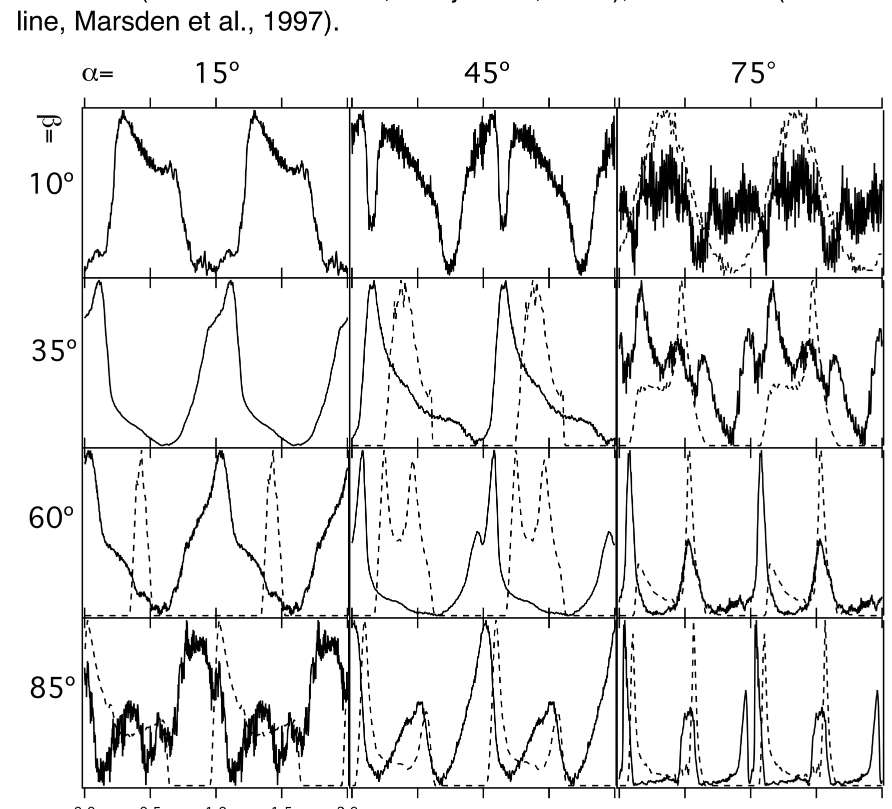
From the null charge surface to the stellar surface, the accelerating electric field is screened out.

Outside the null charge surface, the structure of the gap can be simplified as a two-layer structure (Wang et al., 2010, 2011).

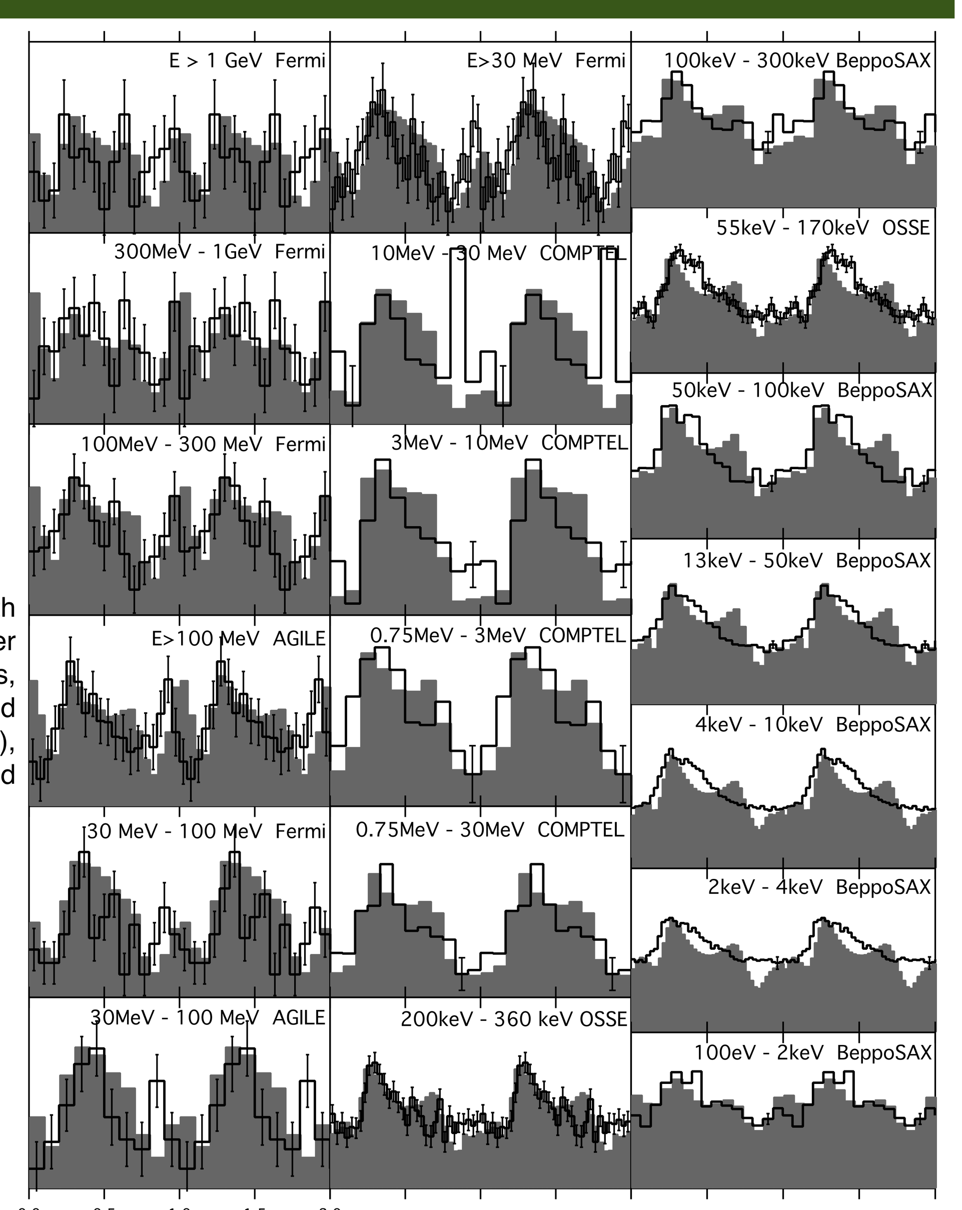
Simulation result:



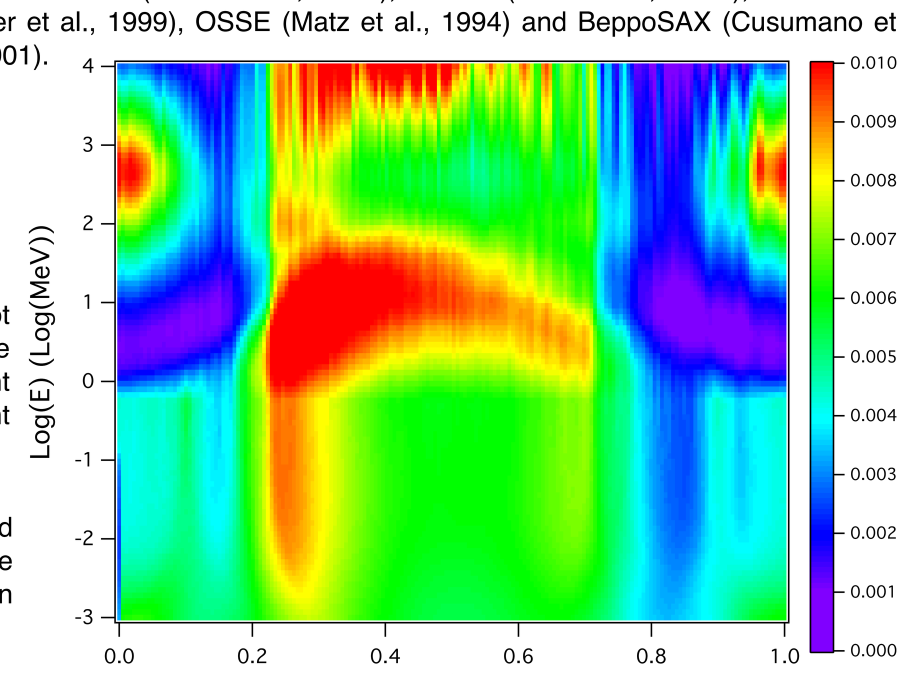
The simulated phase averaged spectrum of PSR B1509, comparing with the observed data provided by EGERT(triangle), COMPTEL (circles, Kuiper et al., 1999), AGILE (filled squares, Pilia et al., 2010), Fermi (diamonds, Abdo et al., 2010), ASCA (dot line, Saito et al., 1997), Ginga (dot-dashed line, Kawai et al., 1992), OSSE (long-dashed line, Matz et al., 1994), Welcome (dot-dot-dashed line, Gunji et al., 1994), and RXTE (short-dashed line, Marsden et al., 1997).



The light curves of the synchrotron radiation (solid lines), which do not consider the attenuation of the original incoming curvature radiation, and the light curves of the outgoing curvature radiation (dashed lines), of different inclination angles and viewing angles. The two types of radiation have different scales in y-axis.



The simulated energy dependent light curves (grey histograms), comparing with the observed data (solid lines), which are provided by Fermi LAT (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).

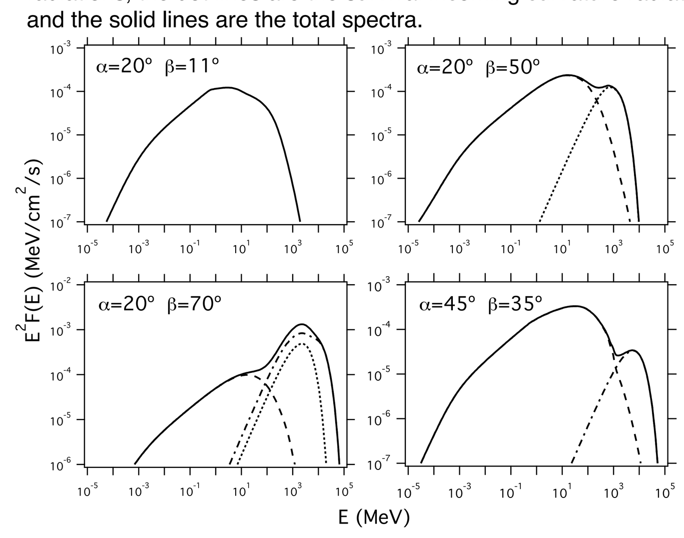


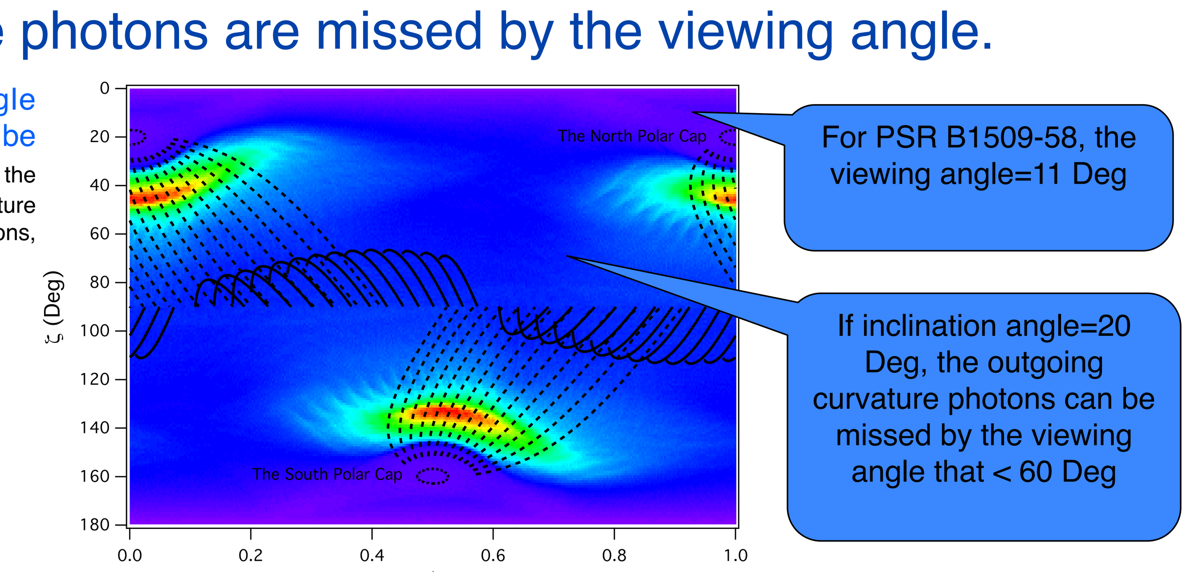
The simulated energy dependent light curves in the pulse phase and energy plane. The color represents the percentage of the number of the photons of certain pulse phase interval, in the total number of photons of certain energy range.

Where are the GeV curvature photons?

The outgoing GeV curvature photons are missed by the viewing angle.

If the viewing angle or inclination angle increases, the GeV curvature photons can be seen. The dashed lines are the synchrotron radiations of the secondary pairs, the dot-dashed lines are the outgoing curvature radiations, the dot lines are the survival incoming curvature radiations, and the solid lines are the total spectra.



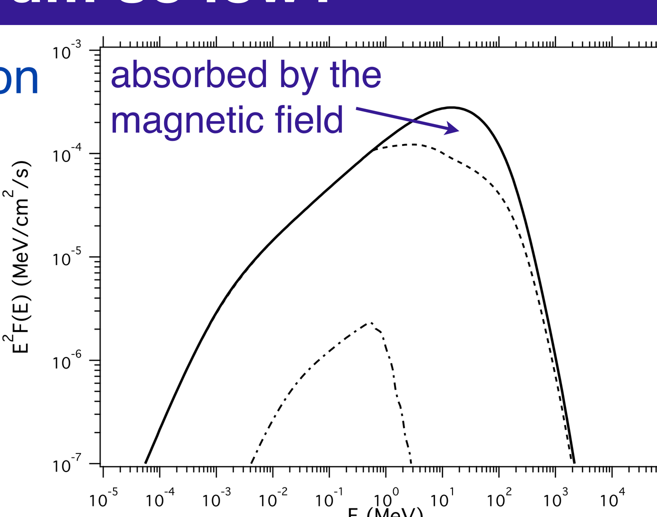


The skymap of the viewing angle and the pulse phase of the outgoing curvature photons (solid line) emitted from the null charge surface to the light cylinder, the incoming curvature photons (dashed line) emitted from the null charge surface to the stellar surface, and the synchrotron photons (color) emitted from the places, where the pair creation happens. The inclination angle =20Deg.

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

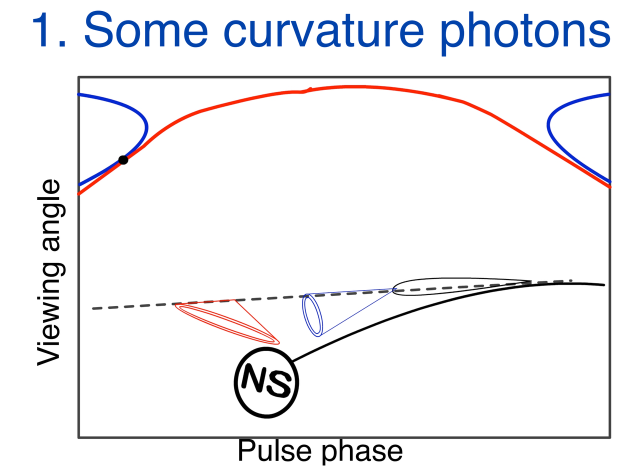
This is because of the attenuation of the synchrotron photons caused by the magnetic pair creation.

The spectra of the synchrotron radiations of the secondary pairs generated by pair creations. The solid line is the one without considering the attenuation of the synchrotron photons by the magnetic pair creation. The dashed line is the spectrum of the survival synchrotron photons from the magnetic pair creation. The dot-dashed line is the contribution of the photon-photon pair creation, which considers the attenuation caused by the magnetic pair creation.



Why is there a second peak at phase~0?

1. Some curvature photons become pairs under smaller pitch angles.

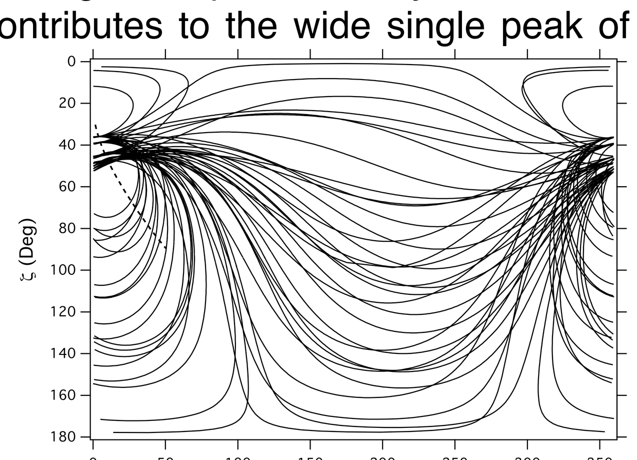


In the skymap, the highly beamed curvature radiation is represented by a **point**,

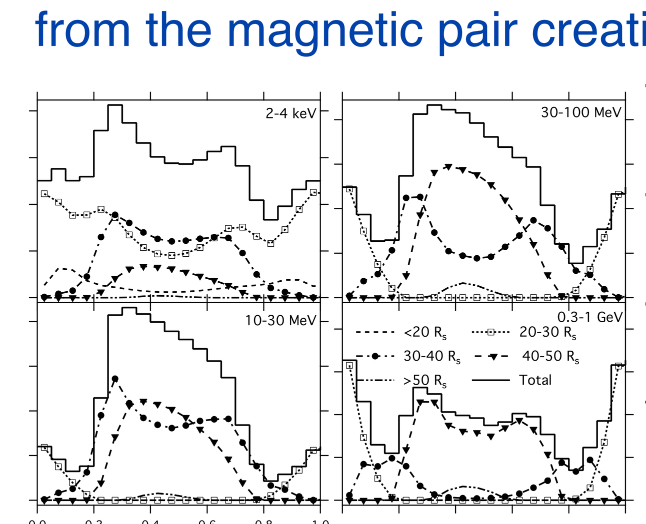
the hollow cone with a small pitch angle is represented by a '**circle**' surrounding the polar cap and contributes to the peak at phase~0,

the hollow cone with a large pitch angle is represented by a '**line**' that goes across the skymap and contributes to the wide single peak of phase 0.25-0.65.

The skymap of the viewing angle ζ and the pulse phase ψ of the synchrotron radiation (solid line) and the incoming curvature radiation (dashed line) originate from one magnetic field line, where the inclination angle=20Deg. The incoming curvature photons, which are represented by the points in the dashed line, are emitted by the particles moving from the null charge surface to the stellar surface along one magnetic field line. And the synchrotron photons are emitted from the places where pair creation happens. Along the directions of the curvature photons, there are many places where the condition of pair creation can be satisfied. The hollow cones of the synchrotron radiation are represented by the solid lines.



2. The synchrotron photon whose phase is closer to 0, has higher chace to survive from the magnetic pair creation.

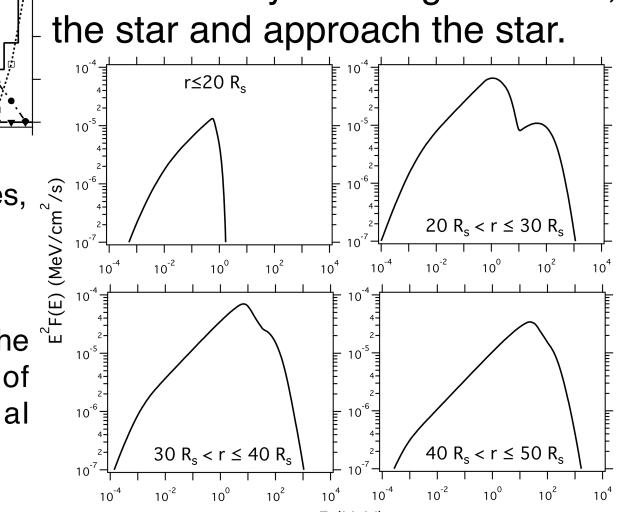


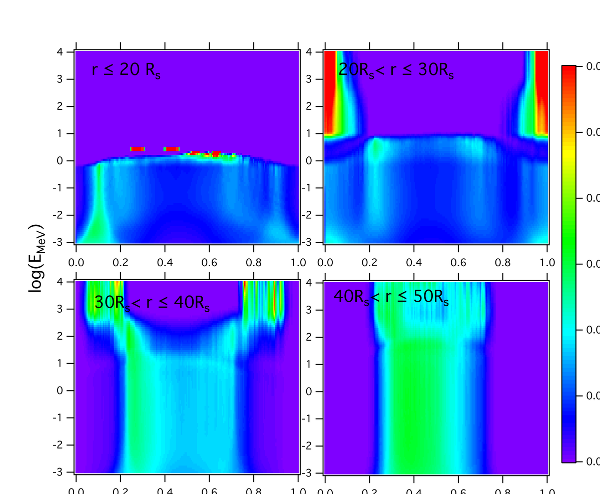
The light curves of different birth places, *r*, of original curvature photons.

The synchrotron photons can also be converted to pairs by the magnetic field.

The second peak's original curvature photons come from the region of 20-30 Rs.

The synchrotron photons, whose phases are close to 0.5, are attenuated by the magnetic field, because they are emitted close to the star and approach the star.





The phase averaged spectra and the energy dependent light curves of different birth places of the original curvature photons.

Why does the second peak show up when energy increases?

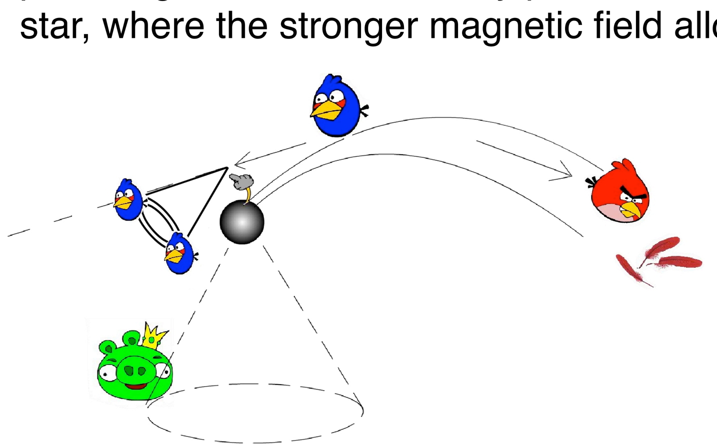
If the particle is made via the magnetic pair creation, the typical energy of its synchrotron radiation is proportional to the energy of its original curvature photon.

The curvature photon with higher energy can become pair under smaller pitch angle, which leads to a pulse 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.

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 incliantion angle=20Deg and viewing angle=11Deg. 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>10MeV 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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THE DETAILS OF THE SIMULATION AND THE DISCUSSION WILL BE GIVEN BY