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Particle Acceleration Above the Pulsar Polar Cap

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Abstract. The constraint on the formation of a polar gap by acceleration in the outer magnetospheric region is discussed.

1. Polar Gap and Outer Gap

Past work on pulsar electrodynamics focused on particle acceleration in two separate regions: the region near the polar cap (PC) — the polar gap (PG) model (e.g., Arons & Scharlemann 1979, hereafter AS; Harding & Muslimov 1998, hereafter HM), and the region in the outer magnetopshere — the outer gap (OG) model (e.g., Cheng, Ho & Ruderman 1986). The PG model is favored by radio observations, while observations of pulsar high energy emission appear to require an OG model.

Acceleration of electrons (positrons) by the parallel electric field above the PC leads to pair production. Here we only consider the case that the outflowing particles are electrons (e^-). As shown in Figure 1, a fraction of positrons (e^+) created in the cascade flow back to the star, resulting in PC heating and modifying the boundary conditions as well as the accelerating electric field (AS; HM). Acceleration in the OG can produce a backflow of relativistic particles, which inject $e^\pm$ into the PG. The injection of $e^\pm$ can strongly affect the stability of the latter, which has not been studied in detail and is considered here.

2. Feedback Due to a Return Flux of Positrons

The existence of a self-consistent steady, parallel accelerating electric field, $E_{||}$, depends critically on the boundary conditions at the surface and pair production front (PPF) (Shibata, Miyazaki & Takahara 2002). The common features of a steady PG is that the accelerating electric field is shorted out at the PPF and a small backflow of positrons provides feedback to the system. These backflowing positrons add positive space charges at the surface, prohibiting outflow of primary electrons (AS; HM). Thus, for a steady gap to exist in the inner magnetosphere, the return flux must be small.

3. The Effects of the Injection of $e^+(e^-)$ on the PG

Apart from the return flux from the PPF, $e^\pm$ can be injected directly from the OG. This generally affects only a small fraction of the PC, corresponding to $\Delta\theta_*/\theta_d \approx [\Delta w_g(\pi/2-\alpha)/6r_c] \ll 1$, where θ_d is the half angle of the PC, α is the inclination angle, Δw_g is the OG thickness, θ_* is the magnetic colatitude, r_c

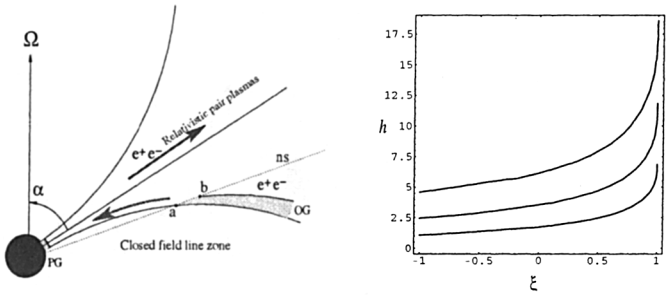

Figure 1. Polar gap (PG) and outer gap (OG). The plots are the distance from the photon path to the PC as a function of $\xi = \pm\theta_*/\theta_d$.

is the radial distance to the inner end of the OG (corresponding to the point a in Fig. 1). All distances are relative to star's radius, R_0.

Injection of $e^{\pm}$ is mainly due to high energy photons emitted by the inward-directed flux of particles. At high altitudes, the main channel for pair production is via $\gamma - \gamma$ collision. The hot PC provides target photons, and the injection of $e^{\pm}$ can cover the whole cross section of the PG. As positrons move toward the star along the curved field lines, they emit photons at a closer radial distance to the star and the propagation angle can be substantial. Thus, photon decay in strong magnetic fields becomes a significant source of backflowing positrons.

A backflow of positrons can limit the outflowing electrons and hence leads to reduction in the production of outflowing pairs. For young pulsars with a large α, the total flux of backflowing positrons $F_+^<$ can be much larger than the critical backflow flux, $\theta_d^2 F_{\rm GJ}$ (where $F_{\rm GJ}$ is the Goldreich-Julian flux), at which the steady polar gap can be disrupted (AS; HM). The injection of positrons generally varies across the gap and hence PC heating by the backflowing positrons must be nonuniform across the cap, which should produce potentially observable features in thermal X-ray emission.

In summary, a self-consistent acceleration model needs to include the effect of the OG. Particle acceleration in the OG produces an inward-directed flux of particles to the PG, resulting in a pair cascade in the inner magnetosphere, injecting $e^{\pm}$ into the inner gap. This injection strongly affects the efficiency of pair production and the stability of the PG. Strong acceleration in the OG occurs in young pulsars with a large inclination angle, leading to a nonstationary PG and inefficient production of outflowing pairs in the inner magnetosphere. The injection of $e^{\pm}$ may cause nonuniform PC heating as the pair cascade that produces backflowing positrons varies across the cap. A detailed model on the effect of the OG on particle acceleration above the PC is currently being explored.

References

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