Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Compton scattering effect on polar gap formation: Self-sustained polar cap heating

Qinghuan Luo

Research Centre for Theoretical Astrophysics, University of Sydney, NSW 2006, Australia

National Institute for Space Research, P.O. Box 515, 12201-970 S.J. Campos-SP, Brazil

1. RICS effect on polar gap

One of the essential ingredients in existing polar gap models (e.g. Ruderman & Sutherland 1975; Arons & Scharlemann 1979, hereafter AS) is a pair cascade above polar caps. In these models, pair cascade is initiated by curvature photons radiated by primary particles and produced pairs screen out the electric field, forming a pair-production-limited acceleration zone (called the polar gap). For pulsars with strong magnetic fields ($B \gtrsim 10^{12}$ G) and hot polar caps, resonant inverse Compton scattering (RICS) can be important (e.g. Dermer 1990; Sturner 1995, and references therein). The gap height is significantly reduced by the RICS effect (Luo 1996), and this may reduce the energetics of the polar gap as the maximum energy of primary particles is constrained by the gap height. The minimum temperature for RICS to be important is (Luo 1996)

$$T_0 \gtrsim (9.2 \times 10^5 \text{ K}) \left(\frac{\ln \Lambda_*}{22}\right)^{-3/2} \left(\frac{\tilde{f}}{16}\right)^{3/2} \left(\frac{B}{5 \times 10^{12} \text{ G}}\right)^{-7/2} \frac{(\sin i)^{1/2}}{P^{1/4}\xi_M}, \qquad (1)$$

where $\ln \Lambda_* \approx 20 \sim 23$, $\tilde{f} \approx 8.12 \sim 16$, P is the pulsar period, i is the angle between the rotation axis and magnetic pole, and $\xi_M \approx \ln(k_B T_0/\varepsilon_{\rm min})$ with $\varepsilon_{\rm min}$ the minimum energy of a photon that satisfies cyclotron resonance condition. Note that $P^{1/4}\xi_M$ is an increasing function as P decreases.

As an example, for pulsar 1509 − 58, including the RICS effect, the gap height (in R_0–the star's radius) is estimated to be $x_0 \approx 0.013$ for $T_0 = 1.5 \times 10^6$ K and $x_0 \approx 0.02$ for $T_0 = 10^6$ K. (Assume $i = \pi/3$.) From the AS model, one has the gap height $x_0^{\rm AS} \approx 0.05$. Since the potential is $\propto x^2$ for $x \lesssim 0.5\theta_c$ ($\theta_c = (2\pi R_0/cP)^{1/2}$) and is $\propto (x+1)^{1/2} - 1$ for $x > 0.5\theta_c$, this implies that the maximum energy that a primary particle can be accelerated to is $\sim 8.5 \times 10^5 mc^2$ for $T_0 = 1.5 \times 10^6$ K and $\sim 2 \times 10^6 mc^2$ for $T_0 = 10^6$ K. This value is well below the threshold for producing curvature photons that are capable of pair production.

For Geminga with $P = 0.237$ s and $B = 1.64 \times 10^{12}$ G, assuming that $T_0 = 3 \times 10^6$ K, one finds $x_0 \approx 0.25$. According to the AS model, Geminga should be near or at the maximum period (for a dipole field). The corresponding gap height is $x_0^{\rm AS} \approx 3.8$. The maximum Lorentz factor of primary particles is $\sim 10^5$, which is one order magnitude smaller than predicted by the AS model.

2. Self-sustained polar cap heating

The existence of a reverse flux of accelerated particles is the natural consequence of imposing a boundary condition on the electric field, i.e. a transition from $\mathbf{E}_{||} \neq 0$ within the gap to $\mathbf{E}_{||} \approx 0$ above the gap (AS). If free emission of electrons from the surface is assumed, the reverse flux is mainly due to trapped positrons in the gap.

If the energy flux impinging on the surface is thermalized rather than conducted away into other parts of the neutron star, the polar cap temperature is estimated to be (e.g. AS)

$$T_h = 1.1 \times 10^5 \text{ K} \left(\frac{x_0}{0.5\theta_c}\right)^{1/4} \left(\frac{\gamma_0}{10^5}\right)^{1/4} \left(\frac{P}{1 \text{ s}}\right)^{-1/2} \left(\frac{B}{10^{12} \text{ G}}\right)^{1/4} (\tan i)^{1/4}, \quad (2)$$

where x_0 is the gap height and γ_0 is the mean Lorentz factor of positrons in the reverse flux at the surface.

The effective temperature due to polar cap heating can be higher than (2) if positron trapping occurs beyond the upper-boundary of the gap (i.e. in the magnetosphere) due to a small residual (parallel) electric fields or if there exists an acceleration zone in the outer magnetospheric region, e.g. the outer gap suggested by Cheng, Ho & Ruderman (1986), in which electrons or positrons (accelerated through the outer gap) may be injected into the polar gap and heat the cap.

When $T_h > T_0$, self-sustained polar cap heating occurs. A pair cascade is started by high energy photons produced through RICS, and polar cap heating enhances the scattering process. The polar cap temperature may saturate at a value close to or higher than (1). This should be the case for young pulsars with strong magnetic fields. At the early phase when pulsar is turned on, the star's surface may be hot and a pair cascade is initiated by RICS photons. As the neutron star cools down, self-sustained polar cap heating is set up and keep the polar cap hot. Pulsar 1509 − 58 is a relevant example. For $x_0 \approx 0.02$ ($T_0 = 10^6$ K), effective temperature of the polar cap due to reverse flux heating is $T = 1.1 \times 10^6 \gtrsim T_0$. If the neutron star's cooling temperature is below $T_0 = 10^6$ K, self-sustained polar cap heating should occur with saturated temperature $\sim 10^6$ K. For the Geminga pulsar, (2) gives $T_h \approx 6.3 \times 10^5$ K, which is well below (1). If there is an injection of positrons from outside the polar gap, i.e. either through positron trapping outside the polar gap or a downward flux of positrons from an outer gap, self-sustained polar cap heating can occur provided that a reverse positron flux is larger than $\xi_r B/(P e)$ ($\xi_r \approx (3/8) x_0 \theta_c \tan i$) by a factor 5×10^2.

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