Observational consequences of the Partially Screened Gap

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Electromagnetic Radiation from Pulsars and Magnetars, 2012
Inner Acceleration Region (IAR)

**Motivation**

**Basic Problem**

**Figure:** Breakdown of the polar gap according to Standard Model (Ruderman & Sutherland 1975)

- **Surface overheating**
  \[ \gamma \approx 3 \times 10^6 \]
  \[ h \approx 20 \text{ m} \]
  \[ T = 4 \text{ MK} \]

- **Observed hot spot area**
  \[ R_{dp} \approx 128 \text{ m} \]
  \[ R_{hs} \approx 30 \text{ m} \]

- Data for PSR B0834+06

Szary et. al (UZ) Partially Screened Gap ERP M 2012
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*Partially Screened Gap*

*ERPM 2012 2 / 16*
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**Surface Overheating Problem**

**Cohesive Energy of Condensed Matter**

**Figure:** Maxwell-Boltzmann distribution of particles energy. Black vertical line corresponds to cohesive energy of condensed matter for magnetic field $B_s = 10^{14}$ G

**Standard model (RS75) assumes that ions cannot be extracted from stellar surface**

If temperature is high enough density of ions is enough to completely screen the gap ($T_s = T_{\text{crit}} \rightarrow \rho_{\text{ions}} = \rho_{\text{GJ}}$)

**Surface temperatures below critical temperature may result in partial screening of the gap ($\rho_{\text{ions}} < \rho_{\text{GJ}}$)**
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Surface temperatures below critical temperature may result in partial screening of the gap ($\rho_{\text{ions}} < \rho_{\text{GJ}}$).
The Condition for the Formation of the Gap

Figure: The condition for the formation of a vacuum gap above condensed helium, carbon, and iron neutron star surfaces (Medin & Lai 2008)
Motivation

Observed Hot Spot Area

Thermal Emission From Isolated Neutron Star

Three blackbody components

\[ T_s = 0.5 - 1 \text{MK} \]
\[ T_{ws} = 2 \text{MK} \quad R_{ws} = 2 \text{km} \]
\[ T_{hs} = 3 \text{MK} \quad R_{hs} = 30 \text{m} \]

Surface magnetic field

\[ B_s = A_{dp}/A_{hs} \cdot B_d \sim 2 \times 10^{14} \text{G} \]

PSG model explains two BB components
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PSG model explains two BB components
Motivation

Non-dipolar Surface Magnetic Field

Figure: Magnetic field lines of NS with crust anchored local anomalies.
**X-ray Observations**

**Figure:** The surface temperature vs. the surface magnetic field. The red line is the critical temperature evaluated from (Medin & Lai 2008).

\[ T_6 = \frac{T_s}{10^6} \quad \text{and} \quad B_{14} = \frac{B_s}{10^{14}} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>( T_6 )</th>
<th>( R_{\text{pc}} )</th>
<th>( B_{14} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0108–1431</td>
<td>3.2( ^\pm )0.41( ^\pm )0.32</td>
<td>6( ^{+4.5}_{-3.7} ) m</td>
<td>3.87( ^{+24.31}_{-2.64} ) m</td>
</tr>
<tr>
<td>B0943+10</td>
<td>3.1( ^\pm )1.08( ^\pm )1.07</td>
<td>12( ^{+41.2}_{-7.7} ) m</td>
<td>4.99( ^{+30.45}_{-4.72} ) m</td>
</tr>
<tr>
<td>B1929+10</td>
<td>4.5( ^\pm )0.30( ^\pm )0.45</td>
<td>28( ^{+4.9}_{-3.8} ) m</td>
<td>1.26( ^{+0.44}_{-0.35} ) m</td>
</tr>
<tr>
<td>B1133+16</td>
<td>3.2( ^\pm )0.46( ^\pm )0.35</td>
<td>14( ^{+10.5}_{-9.0} ) m</td>
<td>4.07( ^{+31.82}_{-2.78} ) m</td>
</tr>
<tr>
<td>B0950+08</td>
<td>2.3( ^\pm )0.29( ^\pm )0.29</td>
<td>42( ^{+26.6}_{-26.6} ) m</td>
<td>0.23( ^{+1.57}_{-0.15} ) m</td>
</tr>
<tr>
<td>B2224+65</td>
<td>5.8( ^\pm )1.16( ^\pm )1.16</td>
<td>28( ^{+5.6}_{-18.0} ) m</td>
<td>2.00( ^{+13.31}_{-0.61} ) m</td>
</tr>
<tr>
<td>J0633+1746</td>
<td>1.7( ^\pm )0.23( ^\pm )0.23</td>
<td>62( ^{+34.0}_{-34.0} ) m</td>
<td>0.75( ^{+2.92}_{-0.44} ) m</td>
</tr>
<tr>
<td>B0834+06</td>
<td>2.0( ^\pm )0.75( ^\pm )0.64</td>
<td>30( ^{+56.4}_{-15.3} ) m</td>
<td>1.05( ^{+3.19}_{-0.92} ) m</td>
</tr>
<tr>
<td>B0355+54</td>
<td>3.0( ^\pm )1.51( ^\pm )1.06</td>
<td>92( ^{+122.5}_{-53.6} ) m</td>
<td>0.27( ^{+1.27}_{-0.22} ) m</td>
</tr>
<tr>
<td>B0628–28</td>
<td>3.3( ^\pm )1.31( ^\pm )0.62</td>
<td>59( ^{+65.5}_{-46.4} ) m</td>
<td>0.29( ^{+5.61}_{-0.22} ) m</td>
</tr>
</tbody>
</table>
Our Results

The Model

Partially Screened Gap

Shielding factor

\[ \eta = 1 - \frac{\rho_{\text{ion}}}{\rho_{\text{GJ}}} \]

Heating condition

\[ \sigma T_s^4 = \eta e \Delta V c n_{\text{GJ}} \]

Acceleration potential drop

\[ \Delta V = \frac{4\pi \eta B_r}{P_C} \cos \alpha h_{\perp}^2 \]
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The Partially Screened Gap Parameters

\[ B_s(T_s), K_6, P, h_\perp \rightarrow \sim h, \eta \leftarrow l_e, l_{acc}, l_{ph} \]
Our Results

The Model

The Partially Screened Gap Parameters

\[ B_s(T_s), \mathcal{R}_6, P, h_{\perp} \quad \rightarrow \quad \sim h, \eta \quad \leftarrow \quad l_e, l_{acc}, l_{ph} \]
Our Results

Drift Model

Drifting Sub-pulse Phenomenon

Figure: Schematic view of the drifting sub-pulse phenomenon showing the periodicities $P_2$ and $P_3$ [Lorimer et al. (2004)].

\[ \mathbf{v}_\perp = c \frac{\mathbf{E} \times \mathbf{B}}{B^2} \]

The existence of IAR in general causes rotation of plasma relative to the NS (drift).

The power spectrum of Radio emission must have a feature due to this plasma rotation.

\[ v_{dr} = \frac{2\pi R_{pc}}{P} \left( \frac{1}{P_3} \frac{P_2^0}{360^\circ} \right) \] (1)
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\[ \nu_{dr} = \frac{2\pi R_{pc}}{P} \left( \frac{1}{P_3} \frac{P_2^\circ}{360^\circ} \right) \quad (1) \]
Our model assumes the existence of plasma columns (sparks) moving (drifting) relative to the NS.

Circulation of the electric field

\[
\oint E \, dl = E_\perp h_\perp + \int_b^c E_\parallel dz + \int_b^c E_\parallel dz = E_\perp h_\perp - V_{cb} = 0
\]

(van Leeuwen & Timokhin 2012)

\[
v_{dr} = c \frac{E_\perp B_r}{B_r^2} = 2\eta \Omega h_\perp \cos \alpha \tag{2}
\]

Figure: Drifting sparks (sub-pulses). All calculations performed in corotating frame of reference ($E_\perp = 0$ just below the stellar surface).
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Drifting Sub-pulses

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![Diagram showing open and closed field lines with a trajectory and labels for the stellar surface and the polar cap.]

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Assuming that the spark width and distance between sparks are of the same order ($h_\perp$)

\[
\frac{P_2^\circ}{360^\circ} \approx \frac{2h_\perp}{2\pi R_{pc}}
\]  

Figure: Cartoon of spark distribution on polar cap. Spark forms when temperature is slightly below critical temperature.
Spark distribution

Assuming that the spark width and distance between sparks are of the same order ($h_{\perp}$)

\[ \frac{P^\circ_2}{360^\circ} \approx \frac{2h_{\perp}}{2\pi R_{pc}} \quad (3) \]

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**Shielding factor**

\[ \eta = \frac{1}{P_3} \frac{1}{2\pi \cos \alpha} \]

**Heating efficiency**

\[ \xi = \frac{L_{\text{heat}}}{L_{sd}} = 0.74578 \left( \frac{1}{P_3} \frac{P^\circ_2}{360^\circ} \right)^2 \]
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### Drift Observations

<table>
<thead>
<tr>
<th>Name</th>
<th>$P_2^\circ$ (deg)</th>
<th>$P_3$ (P)</th>
<th>$\eta$</th>
<th>$\xi$ (radio)</th>
<th>$\xi_{bol}$ (x-ray)</th>
<th>$R_{hs}$ (m)</th>
<th>$h_\perp$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0950+08</td>
<td>–</td>
<td>6.5</td>
<td>0.092</td>
<td>–</td>
<td>$1.5 \times 10^{-4}$</td>
<td>42</td>
<td>–</td>
</tr>
<tr>
<td>B0943+10</td>
<td>18</td>
<td>1.8</td>
<td>0.088</td>
<td>$5.5 \times 10^{-4}$</td>
<td>$2.4 \times 10^{-4}$</td>
<td>12</td>
<td>1.9</td>
</tr>
<tr>
<td>B0834+06</td>
<td>20</td>
<td>2.2</td>
<td>0.148</td>
<td>$4.8 \times 10^{-4}$</td>
<td>$3.9 \times 10^{-4}$</td>
<td>30</td>
<td>5.3</td>
</tr>
<tr>
<td>B0628–28</td>
<td>30</td>
<td>7.0</td>
<td>0.023</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-2}$</td>
<td>59</td>
<td>15.6</td>
</tr>
<tr>
<td>B1929+10</td>
<td>90</td>
<td>9.8</td>
<td>0.020</td>
<td>$4.9 \times 10^{-4}$</td>
<td>$2.9 \times 10^{-4}$</td>
<td>28</td>
<td>21.6</td>
</tr>
<tr>
<td>B1133+16</td>
<td>130</td>
<td>3.0</td>
<td>0.085</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$4.2 \times 10^{-4}$</td>
<td>14</td>
<td>15.4</td>
</tr>
</tbody>
</table>

**Table:** For both B1929+10 and B1133+16 derived period $P_2^\circ$ is not the actual spacing between sub-pulses (its value is greater than pulse width). Large uncertainty in determination of hot spot radius for B0628–28 affects the observed X-ray efficiency.
**Figure:** Non-dipolar structure of magnetic field for PSR B0834+06. Green dashed lines show dipolar open lines, while red lines correspond to actual open magnetic field lines. ($R_6 = 0.5$)
Our Results: Coherent Curvature Radiation (PSR B0834+06)

- **Primary particles**
  \[
  \gamma_{pr} = 1000 - 4000 \quad (l_e = 0.5 \, m)
  \]

- **Secondary particles**
  \[
  \gamma_{sec} = 300 - 1000
  \]

- **Secondary plasma number density**
  \[
  n_{sec} = \eta n_{GJ} M \quad M \approx 10^5 \quad (\text{for } N_{ph} \approx 15)
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Summary

- Combined X-ray and Radio observations allow to put strict constrains on IAR model

- PSG model predicts gap dominated by Inverse Compton Scattering

- ICS dominated gap produces secondary particles suitable for generation of coherent Radio Emission
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