Polarized Surface Emission from Magnetized Neutron Stars

Dong Lai (Cornell University)

Isolated Neutron Stars (T ~ $10^6$-5×$10^6$K)
Accreting X-ray pulsars (T~$10^7$K)

X-ray Polarimetry Workshop, SLAC, 2/2004
Neutron Stars. II. Neutrino-Cooling and Observability

John N. Bahcall and Richard A. Wolf†
California Institute of Technology, Pasadena, California
(Received 19 July 1965)

Calculations of the rates of the cooling reactions \( n + n \rightarrow p + p + \pi - + \nu \) and \( n + p \) are presented; the rates of the closely related muon-producing reactions and the four inversions are used to obtain estimates of the relevant matrix elements. These indicate that a neutron star containing quasifree pions would cool within a few years so that the star would be unobservable. The surface of a star that does not contain cool to \( 10^7 \) K in a few months and would reach \( 4 \times 10^6 \) K in about 100 years. The calculations strongly indicate that the discrete x-ray sources located in the direction of the galactic center...
Thermal (Surface) Radiation from Neutron Stars

Probe the near vicinity and interior of NSs:
- M, R, EOS,
- cooling history (exotic processes),
- surface B and composition

Has been securely detected from ~ 20 sources:
- Radio pulsars
- Radio-quiet NSs (young NSs in SNRs and “dim” Isolated NSs)
- Magnetars (AXPs and SGRs)

Yakovlev et al. 2002
Observations (Chandra, XMM-Newton)

The thermal spectra of many observed NSs are

- featureless (imply light element atmospheres?)
  - Vela pulsar
  - B0656+14
  - B1055-52
  - AXPs …..

- sometimes well fit by blackbody
  - RXJ1856-3754 (“perfect” X-ray BB)

Spectral lines detected in 3-4 sources:

- 1E 1207-5209 (0.7, 1.4 keV; maybe 2.1, 2.8 keV?)
- RXJ1308+2127 (0.2-0.3 keV)
- RXJ1605+3249 (~0.45 keV)
- RXJ0720-3125 (~0.3 keV?)

The full potential of these observations has not been realized:

1. More theoretical work is needed (e.g., Romani, Pavlov-Shibanov, Zane, W. Ho)
2. Source may be complicated (B and geometry): polarization …

Even when spectrum or light curve is boring, polarization can still be interesting
Polarized Surface Emission from Magnetized Neutron Stars

1. Basic polarization signals
2. A surprising signature of QED in polarization signals with Wynn Ho (Cornell/KIPAC)
3. What I think Jeremy Heyl would talk about if he were here

X-ray Polarimetry Workshop, SLAC, 2/2004
Surface emission from magnetic NSs is highly polarized (up to 100%)

Gnedin & Sunyaev 1974
Pavlov & Shibanov 1978
Meszaros et al. 1988
Pavlov & Zavlin 2000
Heyl et al. 2003

......
Photon Polarization Modes in a Magnetized Plasma

($\omega \ll \omega_{ce} = 11.6 \ B_{12} \ \text{keV}$)

**Ordinary Mode (O-mode):**

- $\mathbf{E}$ nearly in the $\mathbf{k}$-$\mathbf{B}$ plane

  \[ |K| = \left| \frac{E_x}{E_y} \right| >> 1 \]

**Extraordinary Mode (X-mode):**

- $\mathbf{E}$ nearly $\perp \mathbf{k}$-$\mathbf{B}$ plane

  \[ |K| = \left| \frac{E_x}{E_y} \right| << 1 \]

The two modes have different opacities (scattering, absorption):

- $\kappa_{\text{(O-mode)}} \sim \kappa_{\text{(B=0)}}$
- $\kappa_{\text{(X-mode)}} \sim \kappa_{\text{(B=0)}} \left( \omega / \omega_{ce} \right)^2$

X-mode photons are the main carrier of X-ray flux

(Two photospheres)
Model by Wynn Ho
Degree of linear Polarization at emission point

$B=10^{13} \text{ G}, \ T_{\text{eff}}=5 \times 10^6 \text{ K}$
Observer
• Polarization vector \( \perp \) the k-B plane (cf. “rotating vector model” for radio pulsars)

  Linear polarization sweep \( \Longrightarrow \) measure the angles

• Polarization signals can be very different even when total intensities are similar
Information Carried by Polarization Signals:

- Geometry (dipole field, rotation axis)
- Dependence on surface field strength
  (e.g., weak polarization in millisecond pulsars)
- Modest dependence on M/R

What if emission is from the whole star? Complex surface field?
Answer: Signals largely unchanged (qualitatively) (Jeremy Heyl’s talk)
Polarization vector \( \perp \) the k-B plane (cf. "rotating vector model" for radio pulsars)

Linear polarization sweep \( \Rightarrow \) measure the angles

Polarization signals can be very different even when total intensities are similar
Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.
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Phase averaged polarization:

$B=10^{13} G$
Vacuum Polarization in Strong B

Heisenberg & Euler 1936, Weisskopf 1936; Schwinger 1951; Adler 1971; Tsai & Erber 1975; Heyl & Hernquist 1997 …..
Vacuum Polarization in Strong B

Dielectric tensor of magnetized plasma including vacuum polarization

\[ \mathcal{E} = \mathcal{I} + \Delta \mathcal{E}^{\text{(plasma)}} + \Delta \mathcal{E}^{\text{(vac)}} \]

where \( \Delta \mathcal{E}^{\text{(vac)}} \sim 10^{-4} (B/B_Q)^2 f(B) \), with \( B_Q = 4.4 \times 10^{13} \text{G}, f(B) \sim 1 \)

Vacuum resonance:

\[ \Delta \mathcal{E}^{\text{(plasma)}} + \Delta \mathcal{E}^{\text{(vac)}} \sim 0 \]

depends on \( -(\omega_p/\omega)^2 \propto \rho/E^2 \)

\[ \rho_{\text{vac}} = 1.0 \ B_{14}^2 \ f(B)^{-1} \ (E/1 \text{ keV})^2 \ \text{g cm}^{-3} \]

At resonance, X-mode and O-mode are “similar”
Property of photon modes

$B=10^{13}$ G, $E=5$ keV, $\theta_B=45^\circ$
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation
Property of photon modes

\[ B = 10^{13} \text{ G}, \ E = 5 \text{ keV}, \ \theta_B = 45^\circ \]
Adiabatic Condition:

\[ |n_1 - n_2| \gtrsim (\cdots) \left| \frac{d\rho}{dr} \right| \]

\[ E \gtrsim E_{ad} = 2.5 \left( \tan \theta_B \right)^{2/3} \left( \frac{1 \text{ cm}}{H} \right)^{1/3} \text{ keV} \]

Photons with $E > 2$ keV, mode conversion

Photons with $E < 2$ keV, no mode conversion

In general, nonadiabatic “jump” probability

\[ P_{\text{jump}} = \exp \left[ -\frac{\pi}{2} (E / E_{ad})^3 \right] \]
For $B < 7 \times 10^{13} T_6^{-1/8} E_1^{-1/4} \, G$:

Vacuum resonance lies outside both photospheres
B=10^{13}G Model

Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.
For $B > 7 \times 10^{13} T_6^{-1/8} E_1^{-1/4}$ G:

Vacuum resonance lies between the two photospheres
Plane of linear polarization at different E coincide.

**B=5×10^{14} G Model**

**B=10^{13} G model**
For $B > 7 \times 10^{13} \, T_6^{-1/8} \, E_1^{-1/4} \, G$:
Spectrum is significantly affected by vacuum polarization effect
Two Examples of AXP Spectra

**AXP 4U0142+61** (Chandra-HETGS)
BB $T=0.4$ keV, power-law $n=3$

**AXP 1E1048-5937** (XMM-Newton)
BB $T=0.6$ keV, Power-law $n=2.9$

Why not see?

 Ion cyclotron absorption $E_{Bi}=0.63$ $B_{14}$ keV

QED at work

Juett et al. 2002; Patel et al 2003

Tiengo et al. 2002
Recapitulation: **Effect of Vacuum Resonance on Thermal Emission**

**For $B<7 \times 10^{13} \text{ G}$** \((\rho_{\text{vac}} < \rho_{\text{o-mode}} < \rho_{\text{x-mode}})\)

- Negligible effect on spectrum
  (spectral line possible: already observed?)
- Dramatic effect on X-ray polarization signals
  (plane of linear polarization depends $E$)
  --- A “clean” QED signature

**For $B>7 \times 10^{13} \text{ G}$** \((\rho_{\text{o-mode}} < \rho_{\text{vac}} < \rho_{\text{x-mode}})\)

- Dramatic effect on spectrum
  (suppress absorption lines, soften hard tails: explain observations of magnetars)
- “Boring” polarization signals
  (plane of linear polarization coincides for different $E$)
Propagation of Polarization from NS Surface to Observer?
What if emission is from the whole star? Complex surface field?

Recall: At the surface, the emergent radiation is dominated by one of the two modes (let’s say X-mode, polarized $\perp$ the local $\mathbf{B}$).

If polarization were parallel-transported to infinity, the net polarization (summed over observable surface of the star) would be reduced.

This is incorrect!
(as first pointed out by Heyl & Shaviv 2002)
Vacuum Polarization in Strong B

Dielectric tensor outside the neutron star: \( \varepsilon = I + \Delta \varepsilon^{(\text{vac})} \)

where \( \Delta \varepsilon^{(\text{vac})} \sim 10^{-4} (B/B_Q)^2 f(B) \), with \( B_Q = 4.4 \times 10^{13} \text{G}, f(B) \sim 1 \)

Modes in magnetized vacuum: linearly polarized
- X-mode
- O-mode

\( n_1 \neq n_2 \)
Propagation of Polarization from NS Surface to Observer Through Magnetized Vacuum

polarization limiting radius $\gg R$

Polarization states of photons from different patches of the star are aligned at large r, and (largely) do not cancel --- Thanks to QED!
Apparent polarization image of a neutron star

No vacuum birefringence

Include vacuum birefringence

Heyl & Shaviv 2002
Summary

• Surface emission from magnetized neutron stars is highly polarized.
• X-ray polarization probes B-fields, geometry, beam patterns, M-R. Complementary to light curve and spectrum (polarization signal may still be interesting even when spectrum is boring.)
• Strong-field QED (vacuum polarization) plays an important role in determining the X-ray polarization signals:
  1. Gives rise to clean energy-dependent polarization signatures
     For $B<7\times10^{13} \text{G}$, the plane of polarization at $E<1 \text{ keV}$ is $\perp$ that at $E>5 \text{ keV}$; For $B>7\times10^{13} \text{G}$, polarization planes coincide (but spectrum is affected).
  2. Aligns the polarization states of photons from different patches of the star so that net polarization remains large.

Probe strong-field QED.
B > 7 \times 10^{13} \text{G regime:}

X-mode O-mode

O-mode X-mode

O-mode Decoupling Layer

Vacuum Resonance

X-mode Decoupling Layer

X-mode O-mode

No Vacuum Effect

X-mode O-mode

With Vacuum Effect
$B = 5 \times 10^{14} \text{G}, \ T_{\text{eff}} = 5 \times 10^6 \text{K}$

$\gamma = 30, \ \beta = 70, \ \psi = 100$
Degree of linear Polarization at emission point
Degree of linear Polarization at emission point

\[ P_L = \frac{I_x - I_o}{I_x + I_o} \]

\[ B = 10^{12} \text{ G, } T_{\text{eff}} = 10^6 \text{ K} \]
Dependence on B:

$E=5$ keV, $\gamma=60$, $\beta=40$

$E=5$ keV, $\gamma=30$, $\beta=70$
1E 1207-5209 in SNR PKS 1209-51/52

$P \approx 0.4 \text{ s, age } \sim 3-20 \text{ kyr, } T_{\text{eff}} = 2 \text{ MK}$

**Clear absorption features at 0.7 and 1.4 keV**
(Sanwal et al. 2002; Mereghetti et al. 2002)

Bignami et al. (2003) claimed additional absorption at 2.1 keV.
3 similar dim isolated NSs (T= 1MK)

Figure provided by
Marten van Kerkwijk (U.Toronto)