Highly Magnetized Neutron Stars and Polarized X-Rays

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Neutron Stars:

Different Observational Manifestations

-- Isolated NSs
-- Accreting NSs
-- Merging NSs
Isolated Neutron Stars

Radio pulsars: \( P, \dot{P} \Rightarrow \)

Most pulsars: \( B \sim 10^{12-13} \text{ G} \)
Millisecond pulsars: \( B \sim 10^{8-9} \text{ G} \)
High – B radio pulsars: \( B \sim 10^{14} \text{ G} \)

Radiation at all wavelengths:
- radio, IR, optical, X-rays, Gamma-rays

New Odd Behaviors:

- RRATs (rotating radio transients)
  - radio bursts (2-30 ms), quiescence (min-hrs);
  - period \( \sim \) sec
- Intermittent Pulsars (“Sometimes a pulsar”)
  - e.g. PSR B1931+24: “on” for \( \sim \) a week,
    “off” for \( \sim \) a month

FRBs??
**Magnetars**

Neutron stars powered by superstrong magnetic fields ($B > 10^{14}$G)

Soft Gamma-Ray Repeaters (SGRs) (7+4 systems)
Anomalous X-ray Pulsars (AXPs) (9+3 systems)

Even in quiescence, $L \sim 10^{34-36}$ erg s$^{-1} \gg I \dot{\Omega}$

AXP/SGR bursts/flares (e.g. Kaspi, Gavriil, Kouveliotou, Woods, etc)

Giant flares in 3 SGRs
- 12/04 flare of SGR1806-20 has $E > 10^{46}$ erg
- QPOs during giant flares (e.g. Israel, Strohmayer, Watts, etc)
Thermally Emitting Isolated NSs

“Perfect” X-ray blackbody:
RX J1856.5-3754

Spectral lines detected:
(e.g., van Kerkwijk & Kaplan 06; Haberl 06)
RXJ1308+2127 (0.2-0.3 keV)
RXJ1605+3249 (~0.45 keV)
RXJ0720-3125 (~0.3 keV)
RXJ0420-5022 (~0.3 keV)?
RXJ0806-4123 (~0.5 keV)?
RBS 1774 (~0.7 keV)?

⇒ $B \sim 10^{13-14}$G? magnetar descendant & off-beam radio pulsar?
Central Compact Objects (CCOs) in SNRs

<table>
<thead>
<tr>
<th>CCO</th>
<th>SNR</th>
<th>Age (kyr)</th>
<th>d (kpc)</th>
<th>P (s)</th>
<th>( f_p^a ) (%)</th>
<th>( B_s ) (10^{11} G)</th>
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<tbody>
<tr>
<td>RX J0822.0 – 4300</td>
<td>Puppis A</td>
<td>3.7</td>
<td>2.2</td>
<td>0.112</td>
<td>11</td>
<td>&lt;9.8</td>
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<tr>
<td>CXOU J085201.4 – 461753</td>
<td>G266.1 – 1.2</td>
<td>1</td>
<td>1</td>
<td>…</td>
<td>&lt;7</td>
<td>…</td>
</tr>
<tr>
<td>1E 1207.4 – 5209</td>
<td>PKS 1209 – 51/52</td>
<td>7</td>
<td>2.2</td>
<td>0.424</td>
<td>9</td>
<td>&lt;3.3</td>
</tr>
<tr>
<td>CXOU J160103.1 – 513353</td>
<td>G330.2 + 1.0</td>
<td>( \geq 3 )</td>
<td>5</td>
<td>…</td>
<td>&lt;40</td>
<td>…</td>
</tr>
<tr>
<td>1WGA J1713.4 – 3949</td>
<td>G347.3 – 0.5</td>
<td>1.6</td>
<td>1.3</td>
<td>…</td>
<td>&lt;7</td>
<td>…</td>
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<tr>
<td>CXOU J185238.6 + 004020</td>
<td>Kes 79</td>
<td>7</td>
<td>7</td>
<td>0.105</td>
<td>64</td>
<td>0.31</td>
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<tr>
<td>CXOU J232327.9 + 584842</td>
<td>Cas A</td>
<td>0.33</td>
<td>3.4</td>
<td>…</td>
<td>&lt;12</td>
<td>…</td>
</tr>
</tbody>
</table>

Small surface dipole field … (are they “anti-magnetars”?)

Halpern & Gotthelf 2010
Hidden Magnetic Fields of Neutron Stars

- NS in Kes 79 SNR has $B_{\text{dipole}} \sim 3 \times 10^{10} \text{ G}$, but large pulse fraction 60\% 

  (Halpern & Gotthelf 2010)

  $\Rightarrow B_{\text{crust}} \sim \text{a few} \times 10^{14} \text{ G}$

  (Shabaltas & DL 2011)

- SGR 0418+5729, with $B_{\text{dipole}} \sim 4 \times 10^{12} \text{ G}$ (Rea et al. 2010)

  $\Rightarrow$ Internal field is much larger (Turolla et al. 2011)
Isolated Neutron Stars (as revealed by X-rays)

-- Radio pulsars
-- Magnetars
-- Other radio-quiet NSs:
  -- Central Compact Objects in SNRs
  -- "Dim" isolated NSs

Future goals:
-- Understand the evolution and links between different types of NSs
-- Understand observed manifestations of these NSs
  (e.g., Radiative processes in NS atmospheres and magnetospheres)
-- Use these NSs to probe physics under extreme conditions
  (e.g., Strong gravity, high density, and strong B fields)

X-ray polarization provides a new window (in addition to spectra/timing)
Even when spectrum or light curve is boring, polarization can still be interesting
Accreting Neutron Stars

-- Non- or weakly magnetized NSs (LMXBs)

-- Highly magnetized NSs (HMXBs)
Puzzle:
Spinup/Spindown of Accreting X-ray pulsars

Bildsten et al. 1997
**4U1626-67**

7.66s

*Transition lasted 150 days*

Camero-Arranz et al. 2010, 2012
kHz QPOs in Accreting Millisecond Pulsars

SAX J1808.4-3658: $\nu_s = 401$ Hz, $\nu_h - \nu_l \simeq \nu_s/2$ (±a few Hz)
XTE J1807.4-294: $\nu_s = 191$ Hz, $\nu_h - \nu_l \simeq \nu_s$
Merging Neutron Stars

NS/NS and NS/BH binaries: GWs for LIGO/VIRGO
EM counterparts (short GRBs, kiloNova)
Merger Simulation with B Fields

Giacomazzo, Rezzolla et al 2011

Palenzuela, Lehner et al. 2013
Merger of Magnetospheres

Hansen & Lyutikov 2001
Consider a binary with
-- magnetic NS (>10^{12}G) + non-magnetic NS
-- embedded in a tenuous plasma (magnetosphere)
EMF : \[ \Phi = 2R_c \left| \frac{v}{c} \times B \right| \]
e.g. \[ \Phi \sim 10^{13} \text{ Volt at } f_{\text{orb}} = 20 \text{ Hz} \]
DC Circuit Powered by Orbital Motion

EMF: \[ \Phi = \frac{2\mu R_c}{ca^2} (\Omega_{\text{orb}} - \Omega_s) \]

Current: \[ I = \frac{\Phi}{\mathcal{R}} \]

Dissipation: \[ \dot{E}_{\text{diss}} = \frac{\Phi^2}{\mathcal{R}} \]
Energy Dissipation in the Magnetosphere of Pre-merging NS Binary

\[ \dot{E}_{\text{max}} \approx 7 \times 10^{44} \left( \frac{B_{\text{NS}}}{10^{13} \text{ G}} \right)^2 \left( \frac{a}{30 \text{ km}} \right)^{-13/2} \text{ erg s}^{-1} \]

- This \( \dot{E} \) will not affect orbital decay rate (GW signal)

- Radio emission prior to binary merger (?) cf. Vietri 96; Hansen & Lyutikov 01

cf. isolated pulsars:

\[ \dot{E} \approx 10^{33} \left( \frac{B_{\text{NS}}}{10^{13} \text{ G}} \right)^2 \left( \frac{P}{1 \text{ s}} \right)^{-4} \text{ erg s}^{-1} \]
Magnetic Fields in the Merger Remnant

Siegel, Ciolfi & Rezzolla 2014

-- Field amplification by differential rotation (MRI resolved?)
-- Wind/outflow
-- Formation of ms magnetar?
Polarized (Surface) X-Rays from Highly Magnetized Neutron Stars

1. Basic polarization signals
2. QED effects in polarization signals
3. Probe axions
Surface emission from magnetic NSs is highly polarized (up to 100%)
Photon Polarization Modes in a Magnetized Plasma

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

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

\[ E \text{ nearly in the } \mathbf{k}-\mathbf{B} \text{ plane} \]
\[ |K| = \left| \frac{E_x}{E_y} \right| >> 1 \]

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

\[ E \text{ nearly } \perp \mathbf{k}-\mathbf{B} \text{ plane} \]
\[ |K| = \left| \frac{E_x}{E_y} \right| << 1 \]

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

\[ K_{(O\text{-mode})} \sim K_{(B=0)} \]
\[ K_{(X\text{-mode})} \sim K_{(B=0)} \left( \frac{\omega}{\omega_{ce}} \right)^2 \]

X-mode photons are the main carrier of X-ray flux
(Two photospheres)
Putting a polarimeter on the NS surface…

Degree of linear Polarization at emission point

\[ \theta_B \]

\[ B=10^{13} \text{ G}, \quad T_{\text{eff}}=5\times10^6 \text{ K} \]

\[ P_L = \frac{(I_x-I_0)/(I_x+I_0)} \]

\[ \theta_B \]

\[ 5 \text{ keV} \]

\[ 2 \text{ keV} \]

\[ 1 \text{ keV} \]

\[ 0.5 \text{ keV} \]
General Expected X-ray Polarization Characteristics

- Polarization vector $\perp$ or $\parallel$ to $\mathbf{k}$-$\mathbf{\mu}$ plane (depending on $\mathbf{E}$ and surface $|\mathbf{B}|$) even when surface field is non-dipole!

- Linear polarization sweep $\Rightarrow$ geometry ("rotating vector model" for radio pulsars)

- Polarization signals can be very different even when total intensities are similar

$$\frac{(Q^2 + U^2)^{1/2}}{I} = \text{Linear Polarization Fraction}$$

$$\frac{Q}{(Q^2 + U^2)^{1/2}} = \cos 2\Phi_P$$
Information Carried by Polarization Signals:

- Geometry (dipole field, rotation axis)
- Dependence on surface field strength
- Modest dependence on M/R
- QED effects
QED Effect: Vacuum Polarization in Strong B

![Diagram of electron and photon](image)

Dielectric tensor:

\[ \epsilon = \mathbf{I} + \Delta \epsilon_{\text{vac}} \]

\[ |\Delta \epsilon_{\text{vac}}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4 \times 10^{13} \text{ G} \]

Two photon modes in magnetized vacuum:
- Ordinary mode (//)
- Extraordinary mode (\(\perp\))

Influence polarization signals in two ways:
1. In NS atmosphere: mode conversion
2. Polarization evolution in magnetosphere: mode decoupling
QED Effect in NS Atmosphere

Dielectric tensor of magnetized plasma including vacuum polarization

$$\varepsilon = I + \Delta\varepsilon^{\text{plasma}} + \Delta\varepsilon^{\text{vac}}$$

where \(\Delta\varepsilon^{\text{vac}} \sim 10^{-4} (B/B_Q)^2 f(B)\), with \(B_Q = 4.4\times10^{13}\)G, \(f(B) \sim 1\)

cf. Gnedin, Pavlov & Shibanov 1978; Meszaros & Ventura 1978, etc

Vacuum resonance:

$$\Delta\varepsilon^{\text{plasma}} + \Delta\varepsilon^{\text{vac}} \sim 0$$

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”
Polarization of photon modes

\[ B = 10^{13} \text{ G}, \ E = 5 \text{ keV}, \ \theta_B = 45^\circ \]
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation
Adiabatic Evolution of a Quantum State
“Plasma+Vacuum” $\Longrightarrow$ Vacuum resonance
Adiabatic Condition:

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

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

Photons with \( E > 2 \text{ keV} \), mode conversion

Photons with \( E < 2 \text{ keV} \), no mode conversion

In general, nonadiabatic “jump” probability

\[ P_{\text{jump}} = \exp \left[ - \left( \frac{\pi}{2} \right) \left( \frac{E}{E_{ad}} \right)^3 \right] \]
Recall

-- X-mode and O-mode have different photospheres

-- $\rho_{\text{vac}} = 1.0 \, B_{14}^2 \, f(B)^{-1} \, (E/1 \text{ keV})^2 \, \text{g cm}^{-3}$
For $B < 7 \times 10^{13} T_6^{-1/8} E_1^{-1/4} G$:

Vacuum resonance lies outside both photospheres
Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.

Van Adelsberg & DL 2006 (also DL & Ho 2003)
For $B > 7 \times 10^{13} T_6^{-1/8} E_1^{-1/4} \text{G}$:

Vacuum resonance lies between the two photospheres.
Plane of linear polarization at different $E$ coincide.
For $B > 7 \times 10^{13} T_6^{-1/8} E_1^{-1/4} \text{G}$:
Spectrum is significantly affected by vacuum polarization effect

\[
B = 5 \times 10^{14} \text{ G} \\
T_{\text{eff}} = 5 \times 10^6 \text{ K}
\]

Proton cyclotron $= 0.63 B_{14} \text{keV}$

With vacuum

No vacuum

$F_V$ (ergs s$^{-1}$ cm$^{-2}$ keV$^{-1}$)

$E$ (keV)
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

**Ion cyclotron absorption** $E_{Bi}=0.63 \, B_{14} \, \text{keV}$

**Why not see?**

**QED at work**
B=7\times10^{13}G Model

\[ B = 7\times10^{13} \text{ G} \]
\[ T_{\text{eff}} = 5\times10^8 \text{ K} \]

\[ F_\text{I} \]
\[ F_\text{Q}/F_\text{I} \]
\[ (F_\text{Q}^2 + F_\text{U}^2)^{1/2}/F_\text{I} \]

Phase

Van Adelsberg & DL 2006
Recapitulation: Effect of Vacuum Resonance on Surface 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: observations of magnetars)
- Polarization signals affected by QED:
  plane of linear polarization coincides for different $E$
QED Effect in Magnetospheres (=Magnetized Vacuum)
Propagation of Polarized Radiation
Propogation of Polarization from NS Surface to Observer

What if emission is from large patch of 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 $B$).

If polarization were parallel-transported to infinity, the net polarization (summed over observable surface of the star) would be reduced.
Propagation of Polarization from NS Surface to Observer
What if emission is from large patch of 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 \( B \)).

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

This is incorrect! (Heyl & Shaviv 2002; Lai & Ho 2003… )
Dielectric tensor outside the neutron star:  $\epsilon = I + \Delta \epsilon^{(\text{vac})}$

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

Two photon modes in magnetized vacuum:
- Ordinary mode ($//$)
- Extraordinary mode ($\perp$)

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

polarization limiting radius >> R

Polarization states of photons from different patches of the star are aligned at large r, and (largely) do not cancel --- Thanks to QED!
But... Propagation through quasi-tangential region

Wang & DL 2009
Polarization map of polar cap (hot spot)

Wang & DL 2009
Reduction of linear polarization due to quasi-tangential propagation

\[ \frac{\tilde{F}}{F_Q} \]

\( \text{Photon energy (keV)} \)

Wang & DL 2009
Polarization map of the whole NS
Propagating Polarization from NS Surface to Observer Through Magnetized Vacuum

Polarization states of photons from **most** region of the NS surface are aligned at large $r$, and do not cancel --- Thanks to QED!

$\Rightarrow$

Observed polarization direction depends only on the dipole component of the field, regardless of surface field structure.

*(Recall: Intensity light curves depend on surface field structure)*
Summary

- Surface emission from magnetized neutron stars is highly polarized.
- X-ray polarization probes B-fields, geometry, beam patterns. Complementary to light curve and spectrum (polarization signal may still be interesting even when spectrum or lightcurve 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 $B<7\times10^{13}$G, the plane of polarization at $E<1$ keV is $\perp$ that at $E>5$ keV;
     For $B>7\times10^{13}$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.
Probing Axions with Magnetic Neutron Stars
Probing Axions with Magnetic NSs

**Axions**: pseudoscalar particles, arise in the Peccei-Quinn solution of the strong CP problem; could be dark matter candidates (1980+)
Recent motivation from string theory

Can be produced or detected through the **Primakoff process**:

\[ \mathcal{L}_{\alpha\gamma} = -\frac{1}{4} g_{\alpha\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{\alpha\gamma} \mathbf{E} \cdot \mathbf{B} a \]

\[ \alpha \rightarrow \gamma \]

\[ \Rightarrow //\text{-component of photon can be coupled to axion} \]
Current constraints on axion mass and coupling parameter
Photon-Axion Conversion in Magnetic Neutron Stars

In the atmosphere and magnetized vacuum of NSs, photons (\ perpendicular\ polarization comp) can convert into axions

$$\Rightarrow \text{modify radiation spectra and polarization signals}$$
Photon-Axion Conversion in Magnetic Neutron Stars

In the atmosphere and magnetized vacuum of NSs, photons (\(//\)-polarization comp) can convert into axions

\[ \Rightarrow \text{modify radiation spectra and polarization signals} \]

\[ D L \ & \ Heyl \ 2007 \]
Photon-Axion Conversion in Magnetic Neutron Stars

In the atmosphere and magnetized vacuum of NSs, photons (//-polarization comp) can convert into axions

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In the atmosphere and magnetized vacuum of NSs, photons (\textit{//}-polarization comp) can convert into axions

\[\Rightarrow\text{ modify radiation spectra and polarization signals}\]

Can in principle probe axions with parameters inaccessible by other experiments/constraints.

Unclear if we can separate out astrophysical uncertainty of the sources.

(cf. Other indirect search of WIMPs)
Thank you!
Power-law emission of magnetars

- Likely due to resonant up-scatterings of surface photons by magnetosphere electrons/positrons (Thompson et al 2002; Fernandez & Thompson 2007)
- Magnetosphere charges (super-GJ) arise from twisting of field lines by crust (Thompson et al 2002; Beloborodov & Thompson 2007; Thompson 2009)

\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}, \quad n_e = J/(ec) \]

- Spectral modeling
  by Fernandez & Thompson 2007 and Nobili et al 2008

- My guess is that the input polarization will be mostly preserved…
Photon-Axion Conversion in Magnetic Neutron Stars

In the atmosphere and magnetized vacuum of NSs, photons (||-polarization comp) can convert into axions

\[ \Rightarrow \text{modify radiation spectra and polarization signals} \]

DL & Heyl 2007