Polarization of Neutron Star Emission and Future X-ray Missions

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The intrinsic polarization

The observed polarization signal: QED (vacuum birefringence) and geometrical effects

Predictions for magnetars and isolated neutron stars

Upcoming X-ray polarimetry missions

What we will measure (and what we have already measured)
Intrinsic polarization

Observed polarization

Predictions

X-ray missions

Measures

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Photon polarization modes

• Radiation emitted by the star surface layers is expected to be polarized because the strong magnetic field
  – Changes the cross-sections and hence the way photons interact with matter
  – Alters the dielectric and (inverse) magnetic permeability tensors and hence affects the way photons propagate

\[ \nabla \times (\tilde{\mu} \cdot \nabla \times E) = \frac{\omega^2}{c^2} \varepsilon \cdot E \]

• In general radiation in a magnetized cold plasma+vacuum is elliptically polarized
• However, for \( \varepsilon \ll E_{ce} \) the two normal modes are almost linearly polarized: the extraordinary (X) and ordinary (O) modes
Photon polarization modes

- O-mode opacity almost unaffected by the magnetic field
- X-mode opacity strongly reduced by a factor $\approx \omega^2/\omega_{ce}^2$
- Intrinsic polarization depends on the surface emission model (and on the possible reprocessing in the magnetosphere)
- Either an atmosphere or a condensed surface (bare NS), maybe covered by a thin H layer (e.g. Potekhin 2014)
Intrinsic polarization of surface emission

Emission properties depend on local $B$ and $T$

Intrinsic polarization

$$\Pi_{EM}^L = \frac{F_X - F_O}{F_X + F_O}$$

Divide the surface into patches and add up those which are in view at a certain phase

Phase-averaged intrinsic polarization (soft X-rays; Gonzalez Canjulef et al. 2016)
<table>
<thead>
<tr>
<th>Intrinsic polarization</th>
<th>Observed polarization</th>
<th>Predictions</th>
<th>X-ray missions</th>
<th>Measures</th>
</tr>
</thead>
</table>

Observed polarization
Stokes parameters

- Wave electric field

\[ E_x = A_x e^{-i(kx-\omega t)} = a_x e^{-i\varphi_x} e^{-i(kx-\omega t)} \]
\[ E_y = A_y e^{-i(ky-\omega t)} = a_y e^{-i\varphi_y} e^{-i(ky-\omega t)} \]

- Polarized radiation conventionally described through the Stokes parameters (that are additive):

\[ I = S_x + S_y = S = a_x^2 + a_y^2 \]
\[ Q = S_x - S_y = A_x A_x^* - A_y A_y^* = S \cos 2\beta \cos 2\chi = a_x^2 - a_y^2 \]
\[ U = A_x A_y^* + A_y A_x^* = 2\Re(A_x A_y^*) = S \cos 2\beta \sin 2\chi = 2a_x a_y \cos(\varphi_x - \varphi_y) \]
\[ V = i(A_x A_y^* - A_y A_x^*) = 2\Im(A_x A_y^*) = S \sin 2\beta = 2a_x a_y \sin(\varphi_x - \varphi_y) \]

- Normalized Stokes vector for linearly polarized radiation: \((1, 0, 0)_x, (-1, 0, 0)_o\)
Each photon is polarized either in the X or O mode with respect to the frame $(x, y, z)$ defined by the propagation vector $\mathbf{k}$ and the local direction of $\mathbf{B}$.

The local frame $(x, y, z)$ changes if $\mathbf{B}$ varies.

Before the Stokes parameters for the entire radiation are computed, they must be referred to the same frame, the polarimeter frame $(u, v, w = z)$.
Stokes parameters rotation

Intrisici polarization  Observed polarization  Predictions  X-ray missions  Measures

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Each photon is polarized either in the X or O mode wrt the frame \((x, y, z)\) defined by the propagation vector \(\mathbf{k}\) and the local direction of \(\mathbf{B}\).

The local frame \((x, y, z)\) changes if \(\mathbf{B}\) varies.

Before the Stokes parameters for the entire radiation are computed they must be referred to the same frame, the polarimeter frame \((u, v, w = z)\).
Stokes parameters rotation

- Under a rotation by an angle $\alpha_i$ the Stokes parameters transform as:

$$I_i = \bar{I}_i \quad Q_i = \bar{Q}_i \cos(2\alpha_i) + \bar{U}_i \sin(2\alpha_i)$$

$$V_i = \bar{V}_i \quad U_i = \bar{U}_i \cos(2\alpha_i) - \bar{Q}_i \sin(2\alpha_i)$$

- The Stokes parameters associated to the whole radiation are given by:

$$Q = \sum_{i}^{N_X} \cos(2\alpha_i) - \sum_{i}^{N_O} \cos(2\alpha_i) \quad U = \sum_{i}^{N_O} \sin(2\alpha_i) - \sum_{i}^{N_X} \sin(2\alpha_i)$$
The polarization properties of NS emission are described by the polarization fraction and polarization angle

\[
\Pi_L = \frac{\sqrt{Q^2 + U^2}}{I}
\]

\[
\chi_p = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)
\]

Only in the case \(\alpha_i = \text{const}\) the observed \(\Pi_L\) and \(\chi_p\) coincide with the intrinsic ones.
Vacuum polarization

- According to QED, a (strong) magnetic field polarizes the vacuum (virtual $e^\pm$ pairs)

- This modifies the $\varepsilon$ and $\mu$ tensors of the vacuum which behaves like a birefringent medium

- By linearizing the wave equation (geometric optics approximation), one obtains a set of ODEs governing the evolution of the complex amplitude of $\mathbf{E}$, $\mathbf{A} = (A_x, A_y, A_z)$
 Vacuum polarization

- Evolution of the Stokes parameters for photons propagating in vacuo (Heyl & Shaviv, 2002; Fernández & Davis, 2011; Taverna et al. 2014))

\[
\frac{d\bar{Q}}{dz} = -\frac{k_0\delta}{2} (2P\bar{V})
\]

\[
\frac{d\bar{U}}{dz} = -\frac{k_0\delta}{2} (N - M)\bar{V}
\]

\[
\frac{d\bar{V}}{dz} = \frac{k_0\delta}{2} [2P\bar{Q} + (N - M)\bar{V}]
\]

\[
k_0 = \frac{\omega}{c}
\]

\[
\ell_A = \frac{2}{\delta k_0 \delta^2} \sim B^{-2} E^{-1}
\]

\[
\ell_B = \frac{B}{|k \cdot VB|}
\]

\[
\ell_A = \ell_B \Rightarrow r_a \approx 4.8 \left( \frac{B_p}{10^{11} \text{ G}} \right)^{2/5} \left( \frac{E}{1 \text{ keV}} \right)^{1/5} R_{NS}
\]

- Two lengthscales
- z coordinate along the ray
- Polarization limiting radius
Evolution of the Stokes parameters for photons propagating in vacuo (Heyl & Shaviv, 2002; Fernández & Davis, 2011; Taverna et al. 2014)

\[
\begin{align*}
\frac{d\mathcal{Q}}{dz} &= -k_0 \delta^2 \nu \mathcal{P}\mathcal{V}
\end{align*}
\]

\[
\begin{align*}
\frac{d\mathcal{U}}{dz} &= -k_0 \delta^2 \mathcal{V} \nu
\end{align*}
\]

\[
\begin{align*}
\frac{d\mathcal{V}}{dz} &= k_0 \delta^2 \mathcal{P}\mathcal{Q} + \mathcal{V} \nu
\end{align*}
\]

Intrinsic polarization

Observed polarization

Predictions

X-ray missions

Measures

Vacuum polarization

\[
\begin{align*}
\ell_A &= 2 k_0 \delta^2 
\end{align*}
\]

\[
\begin{align*}
\ell_B &= \frac{B}{k} \cdot \nabla \sim B^{-2} E^{-1}
\end{align*}
\]

Two lengthscales

\[
\ell_A \ll \ell_B
\]

Adiabatic region

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Evolution of the Stokes parameters for photons propagating in vacuo (Heyl & Shaviv, 2002; Fernández & Davis, 2011; Taverna et al. 2014)

Vacuum polarization

\[ \frac{dQ}{dz} = -k_0 \delta^2 P_{VV} \]

\[ \frac{dU}{dz} = -k_0 \delta^2 N - M \]

\[ \frac{dV}{dz} = k_0 \delta^2 P_{QQ} + N - M \]

Intrinsic polarization

Observed polarization

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Intermediate region

\[ \ell_A \approx \ell_B \]

Two lengthscales

\[ \ell_A = \ell_B \Rightarrow r_{\text{aa}} \approx 4.8 B_{10}^{11} G^{2/5} E_{1 \text{ keV}}^{1/5} R_{N_{17}} \]
Vacuum polarization

\[ \frac{\partial \mathbf{d}_\mathbf{Q}}{\partial z} = -k_0 \delta^2 \frac{\partial P_{\mathbf{Q}}}{} \]

\[ \frac{\partial \mathbf{d}_\mathbf{U}}{\partial z} = -k_0 \delta^2 \mathcal{N} - \mathcal{M} \mathbf{V} \]

\[ \frac{\partial \mathbf{d}_\mathbf{V}}{\partial z} = k_0 \delta^2 \frac{\partial P_{\mathbf{Q}}}{} + \mathcal{N} - \mathcal{M} \mathbf{V} \]

Intrinsic polarization

Observed polarization

Predictions

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Predictions for magnetars and isolated neutron star
Magnetars: persistent

- Magnetar persistent emission: reprocessing of surface thermal radiation by resonant compton scattering onto charges flowing into the twisted magnetosphere
- Scattering changes photon polarization state: \( \sigma_{0-0} = \frac{1}{3} \sigma_{0-x}, \sigma_{x-x} = 3 \sigma_{x-0} \)
- PD and PA depend on twist angle, charge speed and geometrical angles (Fernandez & Davis 2011; Taverna et al. 2014)

Adapted from Taverna et al. (2014)
Magnetars: bursts & flares

- Magnetar bursts/flares originate in a hot, magnetically-confined pair fireball (Thompson & Duncan 1995)
- Solve the radiative transfer for the two modes in the surface fireball layers (Lyubarsky 2002; Taverna & Turolla 2017)
- Because the scattering depth for the O-mode is >> than that for the E-mode, radiation is highly polarized. Spectrum ‘BB+BB’-like (Israel et al. 2007)

More in Roberto Taverna’s talk!
Thermally emitting isolated NSs

- The XDINSs: seven close-by sources with soft thermal spectrum, $kT \approx 50-100$ eV, and period $P \approx 3-12$ s (e.g. Turolla 2009)
- Emission from the entire star surface with an inhomogeneous temperature distribution ($T \sim |\cos \theta|^{1/2}$ for a core-centred dipole)
- Radiation mechanism still uncertain: an atmosphere, a condensed surface?

Phase-averaged polarization fraction (Gonzalez Canjulef et al. 2016)

- H atmosphere
- Condensed surface (fixed ions)
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**X-ray missions**
**X-ray polarimetric missions**

- IXPE (Imaging X-ray Polarimetry Explorer), selected as NASA SMEX mission (launch expected late 2020)
- XIPE (X-ray Imaging Polarimeter Explorer), competing for ESA M4 (if selected launch expected late 2020)
- eXTP (enhanced X-ray Timing and Polarimetry mission), Strategic Priority Space Science Program of the Chinese Academy of Sciences (launch expected within 2025)
## X-ray polarimetric missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Effective area (cm²)</th>
<th>Energy range (keV)</th>
<th>Angular resolution (arcsec)</th>
<th>Polarimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>IXPE</td>
<td><a href="mailto:690@2.3keV">690@2.3keV</a> 3 units</td>
<td>2-8</td>
<td>&lt; 25</td>
<td>GPD</td>
</tr>
<tr>
<td>XIPE</td>
<td>&gt; 1100@3keV 3 units</td>
<td>2-8</td>
<td>&lt; 30</td>
<td>GPD</td>
</tr>
<tr>
<td>eXTP</td>
<td>900@2keV 4 units</td>
<td>2-10</td>
<td>&lt; 30</td>
<td>GPD</td>
</tr>
</tbody>
</table>

The three missions use the same Gas Pixel Detector polarimeter developed by INAF-IAPS (GPD; Costa et al. 2001; Bellazzini et al. 2005; Fabiani et al. 2014)
Gas pixel detector

- Detection uses photoelectric effect
- X-rays absorbed in detector fill gas
- Photoelectron emission aligned with X-ray polarization vector
- Electron multiplier with pixelated detector
- Analysis of the distribution of the initial directions of the tracks gives the degree of polarization and the position angle for the incident X-ray
What we will measure (and what we have already measured)
Magnetsars: persistent

XIPE and IXPE simulations for a bright magnetar source (AXP 1RXS J1708)

- Phase-resolved polarimetry can probe the RCS model and pinpoint the source geometry and physical parameters (spectroscopy alone cannot)
- X-ray polarimetry can univocally detect vacuum polarization, an effect still to be experimentally observed

<table>
<thead>
<tr>
<th>Input value</th>
<th>Fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>$0.34 \pm 0.007$</td>
</tr>
<tr>
<td>$\Delta \phi_{N-S}$ (rad)</td>
<td>$0.47 \pm 0.013$</td>
</tr>
<tr>
<td>$\chi$ (deg)</td>
<td>$91.68 \pm 2.56$</td>
</tr>
<tr>
<td>$\xi$ (deg)</td>
<td>$59.64 \pm 1.08$</td>
</tr>
<tr>
<td>$X^2_{\text{rad}}$</td>
<td>$11.40$</td>
</tr>
</tbody>
</table>
Magnetars: bursts & flares

- Polarimetry will get insight on the physical processes at work in bursts
- Simulations for the intermediate flare IF1 from SRG 1900+14 (Israel et al. 2007; Taverna & Turolla 2017)
Thermally emitting INSs

- Thermal emission from the XDINSs too soft for the GPD. Need to wait for future soft X-ray polarimeters (e.g. Marshall et al. 2015)
- Phase-averaged polarization fraction (Taverna et al. 2015)
Observations of the XDINS RX J1856 in the B band with the VLT revealed a relatively high polarization degree, $16.43 \pm 5.26\%$ (Mignani et al. 2017).
Vacuum polarization detected in the optical?

- Current surface emission models hardly compatible with such a high polarization degree **if no QED effects are accounted for** when constraints from the X-ray pulsed fraction are included.

![Diagram](image)

- Magnetic H atmosphere
- Condensed surface (fixed ions)
Vacuum polarization detected in the optical?

- On the other hand they work quite well when vacuum polarization is there!
Conclusions
Conclusions

• X-ray polarimeters will target several magnetar sources, allowing a firm detection of vacuum birefringence

• Polarization measurements will provide crucial tests for current models for magnetar persistent and bursting emission

• Future missions will extend polarimetry to the soft X-ray band and target thermally emitting INSs, probing their emission mechanism and providing further checks of vacuum birefringence