X-ray Polarization and Fundamental Physics

High-throughput X-ray Astronomy in the eXTP Era

Jeremy S. Heyl

7 February 2017

Ilaria Caiazzo, Rosalba Perna, Roberto Turolla, Roberto Taverna and others.

Outline

The Low-Energy Frontier

- With the discovery of the Higgs, what is left to discover in the standard model and what needs to change?

The Low-Energy Frontier

- With the discovery of the Higgs, what is left to discover in the standard model and what needs to change?
- At low energies, we have neutrino masses (Dirac/Majorana/sterile)

The Low-Energy Frontier

- With the discovery of the Higgs, what is left to discover in the standard model and what needs to change?
- At low energies, we have neutrino masses (Dirac/Majorana/sterile)
- CP-violation in QCD

The Low-Energy Frontier

- With the discovery of the Higgs, what is left to discover in the standard model and what needs to change?
- At low energies, we have neutrino masses (Dirac/Majorana/sterile)
- *CP*-violation in QCD
- Charge radius of protons differs between muons and electrons.

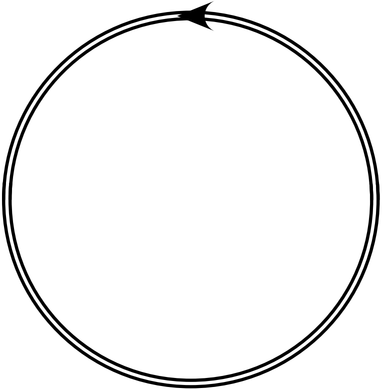
The Low-Energy Frontier

- With the discovery of the Higgs, what is left to discover in the standard model and what needs to change?
- At low energies, we have neutrino masses (Dirac/Majorana/sterile)
- *CP*-violation in QCD
- Charge radius of protons differs between muons and electrons.
- Muon $g-2$

The Low-Energy Frontier

- With the discovery of the Higgs, what is left to discover in the standard model and what needs to change?
- At low energies, we have neutrino masses (Dirac/Majorana/sterile)
- CP-violation in QCD
- Charge radius of protons differs between muons and electrons.
- Muon $g - 2$
- Non-linear interaction of light with light.

Effective Action



For a magnetic field the effective action is the free energy of the system (actually minus the free energy).

$$\Gamma[A^0_\mu] = \int \mathrm{d}x^4 \left(-\frac{1}{4} F^0_{\mu\nu} F^{0,\mu\nu} \right) - i\hbar \mathrm{Tr} \ln \left[\frac{\not{\Pi} - m}{\not{p} - m} \right]$$

The QED Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{\hbar}{8\pi^2} B_k^2 \int_0^\infty \frac{d\zeta}{\zeta} e^{-i\zeta} \left[\frac{ab}{B_k^2} \coth\left(\zeta \frac{a}{B_k}\right) \cot\left(\zeta \frac{b}{B_k}\right) - \mathrm{CT} \right]$$

where

$$(b - ia)^2 = (\mathbf{B} - i\mathbf{E})^2 = |\mathbf{B}|^2 - |\mathbf{E}|^2 - 2i\mathbf{E}\cdot\mathbf{B}$$

$$\left[2(b-ia)^2\right] = F^{\mu\nu}F_{\mu\nu} + i\epsilon_{\mu\nu\alpha\beta}F^{\mu\nu}F^{\alpha\beta} \equiv I + iJ$$

and

$$\mathrm{CT} = \frac{1}{\zeta^2} + \frac{1}{3}\frac{a^2 - b^2}{B_k^2}(a^2 - b^2)$$

Heisenberg-Euler, Weisskopf, Schwinger

Field and Photons

To understand the interaction of light with the magnetized vacuum, we imagine expanding the action for a uniform field plus a small photon field,

$$\mathbf{E} = \mathbf{E}_0 + \delta\mathbf{E}, \mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}, F^{\mu\nu} = (F_0)^{\mu\nu} + f^{\mu\nu}.$$

We have two possibilities.

1. $k\lambda\!\!\!^{-}_e \ll 1$: we pretend that the photon field is also uniform and expand the effective Lagrangian density.

Field and Photons

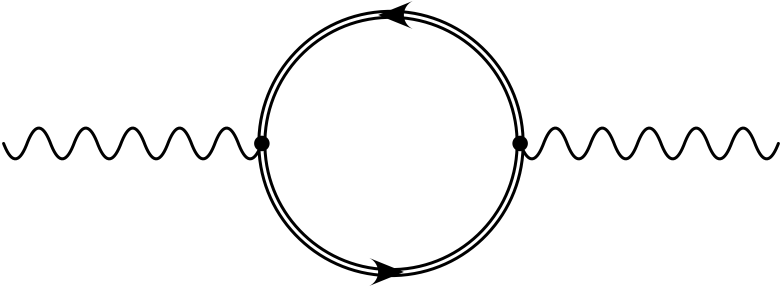
To understand the interaction of light with the magnetized vacuum, we imagine expanding the action for a uniform field plus a small photon field,

$$\mathbf{E} = \mathbf{E}_0 + \delta\mathbf{E}, \mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}, F^{\mu\nu} = (F_0)^{\mu\nu} + f^{\mu\nu}.$$

We have two possibilities.

1. $k\lambda\!\!\!^{-}_e \ll 1$: we pretend that the photon field is also uniform and expand the effective Lagrangian density.
2. $k\lambda\!\!\!^{-}_e \gtrsim 1$: we have to expand the action itself.

How It Works



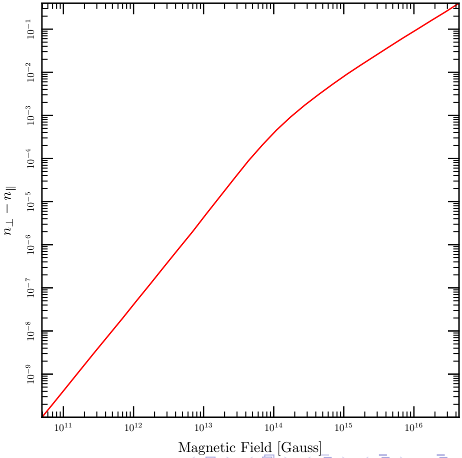
$$S = S_0 + \frac{1}{2} f^{\mu\nu} f^{\alpha\beta} \frac{\delta^2 S}{\delta f^{\mu\nu} \delta f^{\alpha\beta}}$$

Index of Refraction

$$\Delta n = 4 \times 10^{-24} \mathrm{T}^{-2} B^2$$

What could be a signature of this birefringence?

- A time delay: $\Delta t \sim 10^{-3} R/c \sim 10\mathrm{ns}$?

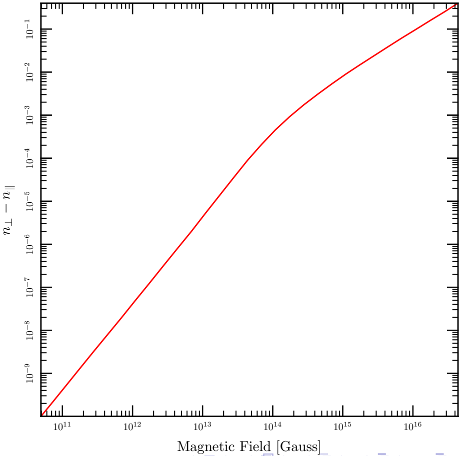


Index of Refraction

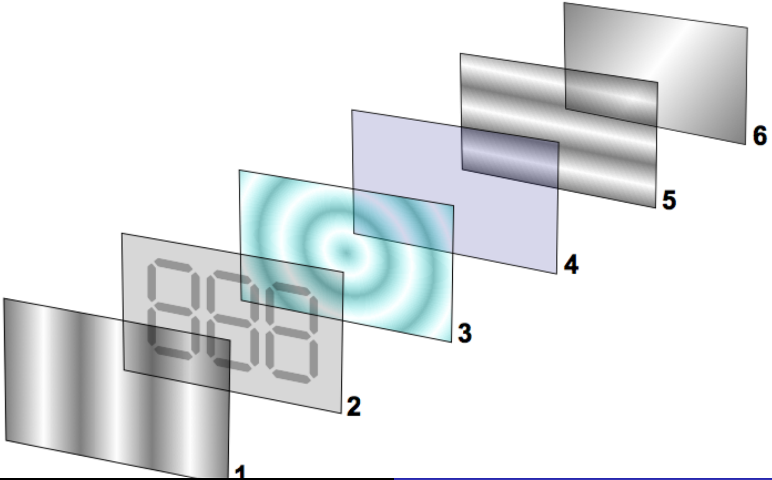
$$\Delta n = 4 \times 10^{-24} \mathrm{T}^{-2} B^2$$

What could be a signature of this birefringence?

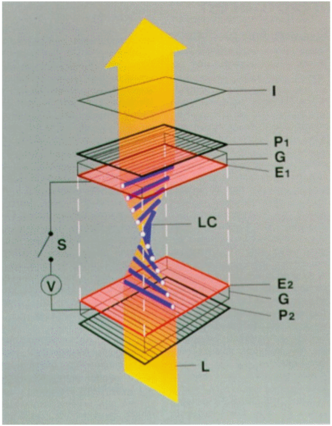
- A time delay: $\Delta t \sim 10^{-3} R/c \sim 10\mathrm{ns}$?
- This seems a bit too subtle.

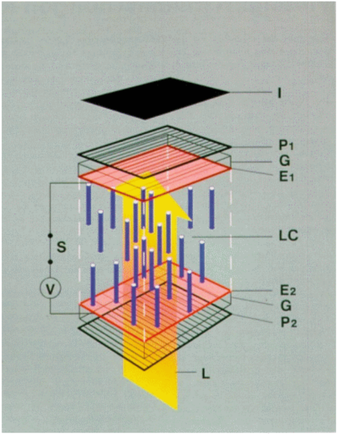


Liquid Crystal Displays



Liquid Crystal Displays





Wikipedia

Propagation through a twisting magnetic field

Kubo and Nagata (1983) present a concise way to characterize the evolution of the polarization of light through a medium; they simply write an equation to track the four Stokes parameters of the polarization light.

$$\frac{\partial \mathbf{s}}{\partial l} = \hat{\mathbf{\Omega}} \times \mathbf{s}$$

where $\left|\hat{\mathbf{\Omega}}\right| = \Delta k$. The vector $\mathbf{s} = (S_1, S_2, S_3)/S_0$ or $(Q, U, V)/I$.

Stokes Parameters and the Poincaré Sphere

An important analytic solution.

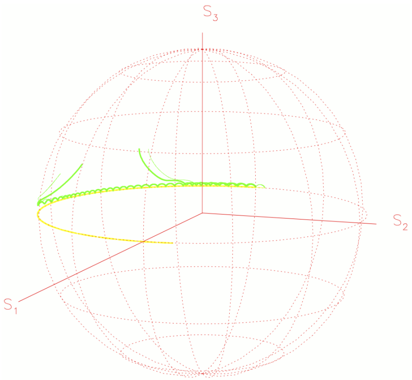
What if $\frac{\partial \hat{\mathbf{\Omega}}}{\partial l} = \hat{\mathbf{\Upsilon}} \times \hat{\mathbf{\Omega}}$?

1. Move into frame that corotates with $\hat{\mathbf{\Omega}}$.
2. In this frame we have

$$\frac{\partial \mathbf{s}}{\partial l} = \left(\hat{\mathbf{\Omega}} - \hat{\mathbf{\Upsilon}}\right) \times \mathbf{s}$$

3. $\mathbf{s}$ orbits $\hat{\mathbf{\Omega}}_{\rm Eff}$ if

$$\left| \hat{\mathbf{\Omega}} \left(\frac{1}{|\hat{\mathbf{\Omega}}|} \frac{\partial |\hat{\mathbf{\Omega}}|}{\partial l} \right)^{-1} \right| \gtrsim 0.5$$



Heyl, Shaviv 00

Polarization-Limiting Radius

The radius at which the polarization stops following the birefringence is called the polarization-limiting radius. Beyond here the modes are coupled.

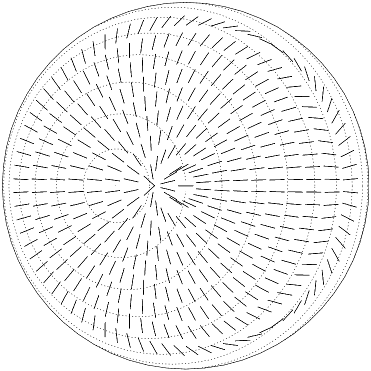
Polarization-Limiting Radius

The radius at which the polarization stops following the birefringence is called the polarization-limiting radius. Beyond here the modes are coupled.

The polarization-limiting radius for a dipole field is

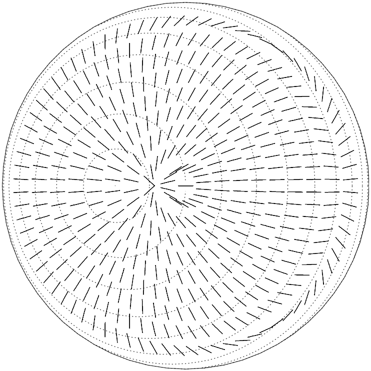
$$\begin{aligned} r_{\rm pl} &\equiv \left(\frac{\alpha}{45}\frac{\nu}{c}\right)^{1/5}\left(\frac{\mu}{B_{\rm QED}}\sin\beta\right)^{2/5} \\ &\approx 1.9\times10^7\left(\frac{\mu}{10^{30}\ \mathrm{G\ cm}^3}\right)^{2/5}\left(\frac{E}{4\ \mathrm{keV}}\right)^{1/5}(\sin\beta)^{2/5}\,\mathrm{cm}, \end{aligned}$$

Why does this matter?

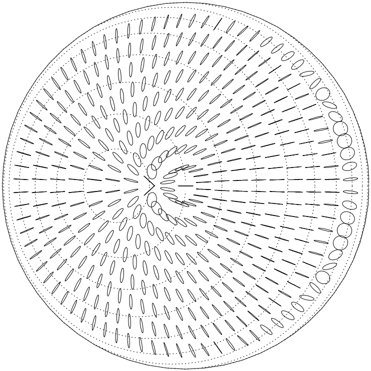


$r_{\mathrm{pl}}/R = 0$
Heyl, Shaviv, Lloyd 03

Why does this matter?

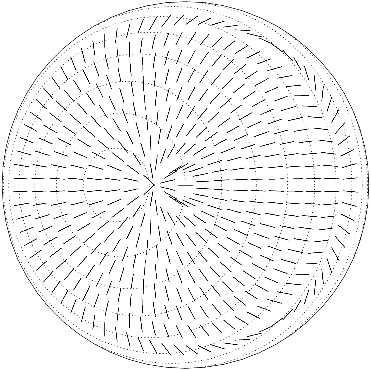


$r_{\mathrm{pl}}/R = 0$
Heyl, Shaviv, Lloyd 03



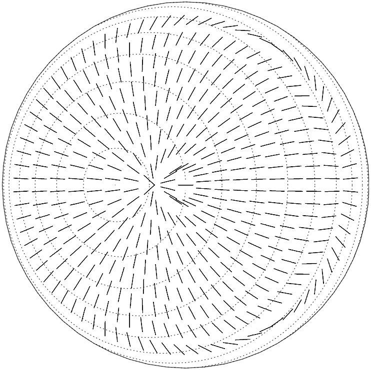
$r_{\mathrm{pl}}/R = 1.9$ (AM Her, AMSP)

Why does this matter?

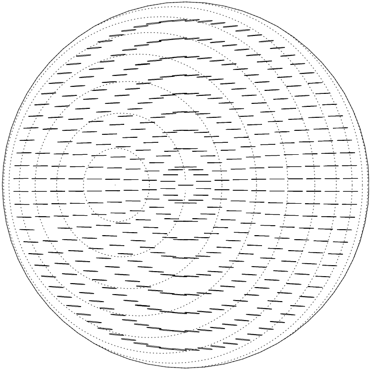


$r_{\rm pl}/R = 0$
Heyl, Shaviv, Lloyd 03

Why does this matter?



$r_{\rm pl}/R = 0$
Heyl, Shaviv, Lloyd 03



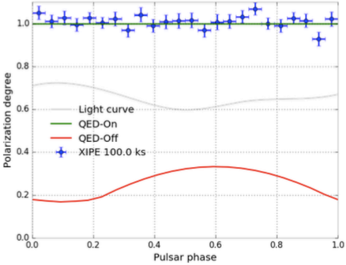
$r_{\rm pl}/R = 76$ (Magnetar)

Places to Look

	Radius	Magnetic Field	μ_{30}	$r_{\rm pl}$ at 4 keV
Magnetar	10^6	10^{15}	10^{33}	3.0×10^8
ms XRP	10^6	10^9	10^{27}	1.2×10^6
AM Her	10^9	10^8	10^{35}	1.9×10^9

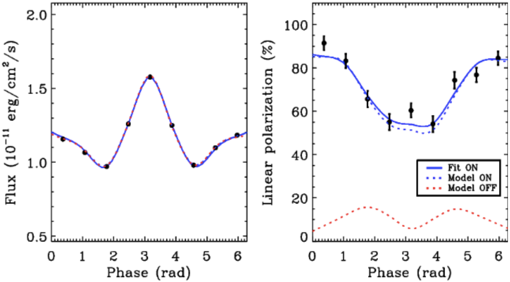
Magnetar Emission

Thermal



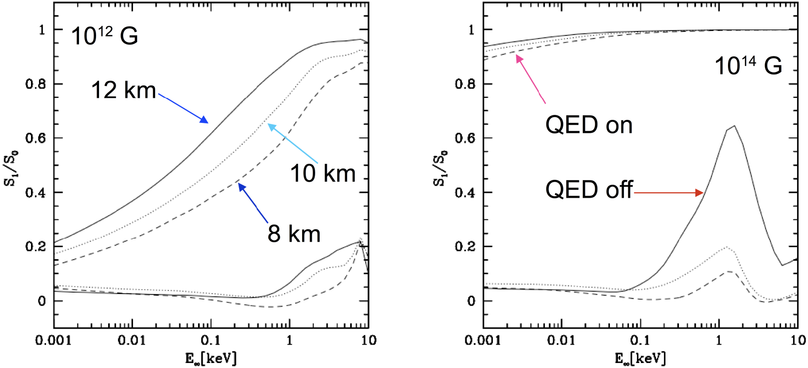
Caiazzo & Heyl 2016; 4U 0142+61

Non-thermal



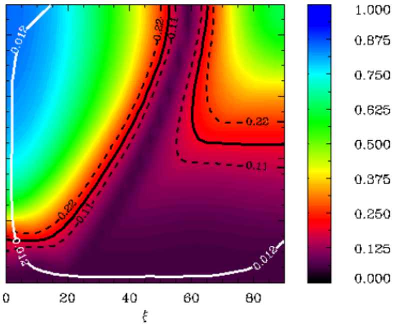
Taverna et al. 2016; SGR 1806-20 (350ks)

Realistic Hydrogen Atmosphere

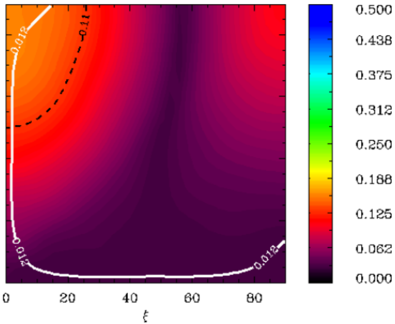


Heyl, Shaviv, Lloyd 03

RX J1856.5-3754



Mignami et al. 2016



Places to Look

	Radius	Magnetic Field	μ_{30}	$r_{\rm pl}$ at 4 keV
Magnetar	10^6	10^{15}	10^{33}	3.0×10^8
ms XRP	10^6	10^9	10^{27}	1.2×10^6
AM Her	10^9	10^8	10^{35}	1.9×10^9

Places to Look

	Radius	Magnetic Field	μ_{30}	$r_{\rm pl}$ at 4 keV
Magnetar	10^6	10^{15}	10^{33}	3.0×10^8
ms XRP	10^6	10^9	10^{27}	1.2×10^6
AM Her	10^9	10^8	10^{35}	1.9×10^9
XRP	10^6	10^{12}	10^{30}	See Ilaria's talk
Black Hole	10^{6+}	?	N/A	