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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Dipartimento di Fisica e Astronomia
UNIVERSITÀ DEGLI STUDI DI PADOVA

THE ASTROPHYSICAL JOURNAL, 324:899–906, 1988 January 15

RADIATIVELY DRIVEN WINI
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Received 1986 I

A sequence of chemically homogeneous, dyna model is computed by fitting onto a helium-bu an expanding atmosphere in which line accele determines all the properties of the configuratio as a function of the total mass M. Although the mainly due to line driving, dynamics is found t radius where only the gradients of isotropic ra derived values of $\dot{M}$ and v_∞ are in good agreem ticular, the $\dot{M}$ versus M relation derived by Abb
Subject headings: Stars: atmospheres — stars: m

I. INTRODUCTION

Line-driven wind models (Castor, Abbott, and Klein 1 Pauldrach, Puls, and Kudritzki 1986; hereafter CAK PPK, respectively; Abbott 1982*a*; Friend and Castor, 1

Astron. Astrophys. 231, 85–88 (1990)

ASTRONOMY AND ASTROPHYSICS

An analytical approach to the problem of mass loss from Wolf-Rayet stars

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Abstract. The dependence of the wind parameters on the properties of the parent star is investigated by means of an approximate analytical approach. In particular, using a polytropic stellar model and line driving as the mechanism for accelerating the wind, it is shown that mass loss from WR stars can be characterized just by the total mass. The existence of a correlation between mass and mass loss rate, which is close to that one found by Abbott et al. (1986) for WR stars in binary systems, $\dot{M} \propto M_*^{2.3}$, seems to be an intrinsic feature of radiative wind acceleration in He-burning stars.

Key words: stars: Wolf-Rayet – stars: mass loss

1. Introduction

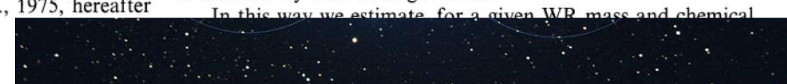
Wolf-Rayet (WR) stellar winds can be accelerated by line driving. Models of line driven winds, which have been developed to explain the mass loss from OB stars (e.g. Castor et al., 1975, hereafter

$\dot{M}$ relation is connected with some details of their input physics or instead it reflects some basic feature of radiative acceleration in He-burning stars. In particular one can ask to what extent some rather crude assumptions, like the core-halo structure for the wind, reflect on the dependence of the mass loss rate on the stellar mass.

This work must be intended as a continuation of TNC, from which we derive many assumptions and parameters, and its scope is to examine in which way WR winds depend on the stellar parameters. To get insight on this dependence an analytical approach, even if rather crude, is useful to complement a numerical one. To this purpose we shall use a very simple model, largely based upon dimensional arguments. Most of the simplifications introduced with respect to TNC consist into:

(a) transforming differential equations into algebraic ones, by taking logarithmic derivatives equal to unity;
(b) dropping into the equations all the negligible terms;
(c) substituting quantities which are function of the radial coordinate by their average values.

In this way we estimate, for a given WR mass and chemical



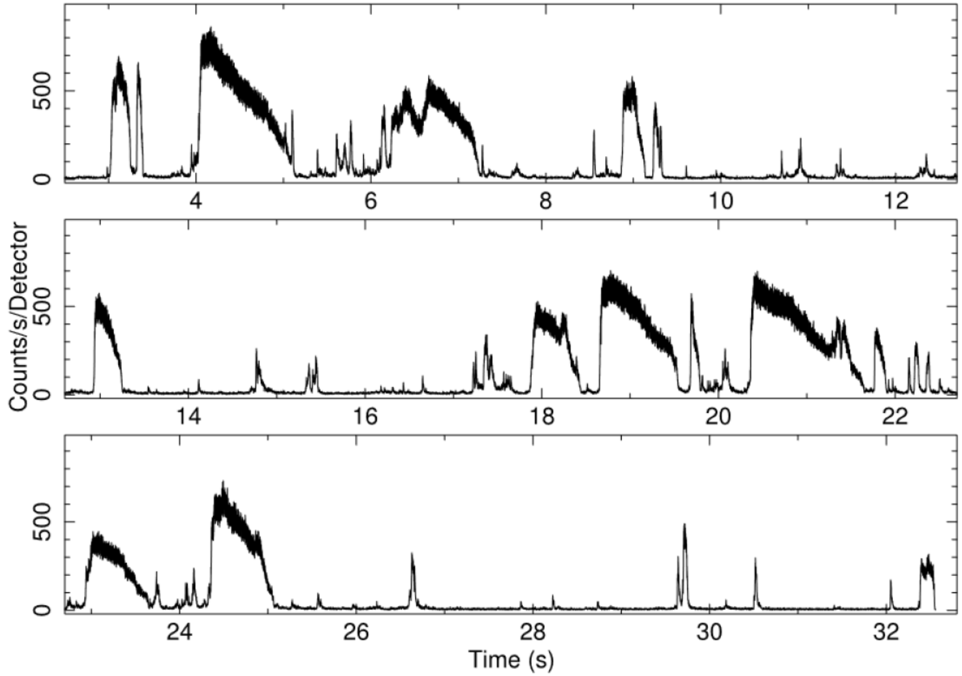
Overview

- Soft γ-repeaters and Anomalous X-ray Pulsars
- Ultra-magnetized NSs aka magnetars
- Persistent X-ray emission from magnetars
- X-ray polarimetry: IXPE
- IXPE and magnetars

Soft Gamma Repeaters - I

Rare class of sources, discovered through the emission of strong, recurrent (whence the name) bursts of soft γ-/hard X-rays:

$L \approx 10^{36}$-10^{44} erg/s >> L_{Edd}, duration 0.1 - 10 s



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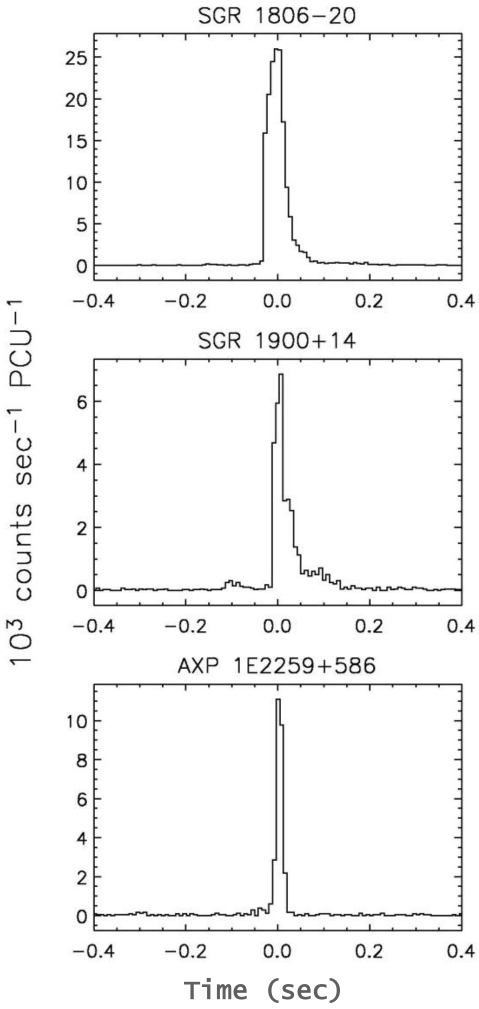
Israel et al. (2008)

Soft Gamma Repeaters - II

- Much more energetic "Giant Flares" (GFs, L ≈ 10^{44} - 10^{47} erg/s, t_{peak} ~ 1 s, t_{tail} ~ 300 s) detected from 3 sources
- No evidence for a binary companion, association with a SNR in a few cases (?)
- Persistent X-ray emitters, L ≈ 10^{33} -10^{35} erg/s
- Pulsations discovered both in GFs tails and persistent emission, P ≈ 2 -10 s
- Huge spin-down rates, as compared to PSRs, $\dot{P}$ ≈ 10^{-11} - 10^{-10} ss^{-1}

Anomalous X-ray Pulsars

- Peculiar class of persistent X-ray sourc erg/s
- Spin-down luminosity $\dot{E} < L_X$ (not powe hence "anomalous")
- Pulsations with P ≈ 2 -10 s
- Large spin-down rates, $\dot{P} \approx 10^{-11}\ ss^{-1}$
- No evidence for a binary companion, as SNR in six (?) cases
- Bursts of soft γ-/hard X-rays quite simil SGRs detected first in AXP 1E 2259+5 2002; Kaspi et al. 2003) and then in all



Magnetars

- Strong convection in a rapidly rotating (P ~ 1 ms) newborn neutron star generates a very strong magnetic field via dynamo action
- Magnetars: neutron stars powered by their own magnetic energy (surface field B > a few $B_Q \sim 10^{14}$ G; Duncan & Thomson 1992; Thomson & Duncan 1993)
- Rapid spin-down due to magneto-dipolar losses, $\dot{P} = 10^{-11}(B/10^{14}\ \mathrm{G})^2 P^{-1}\ \mathrm{s/s}$

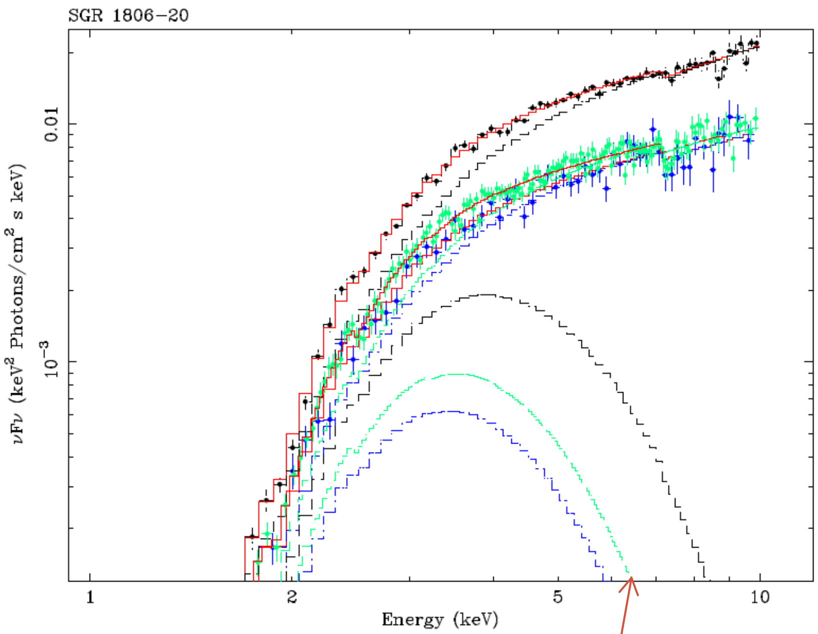
Why magnetars ?

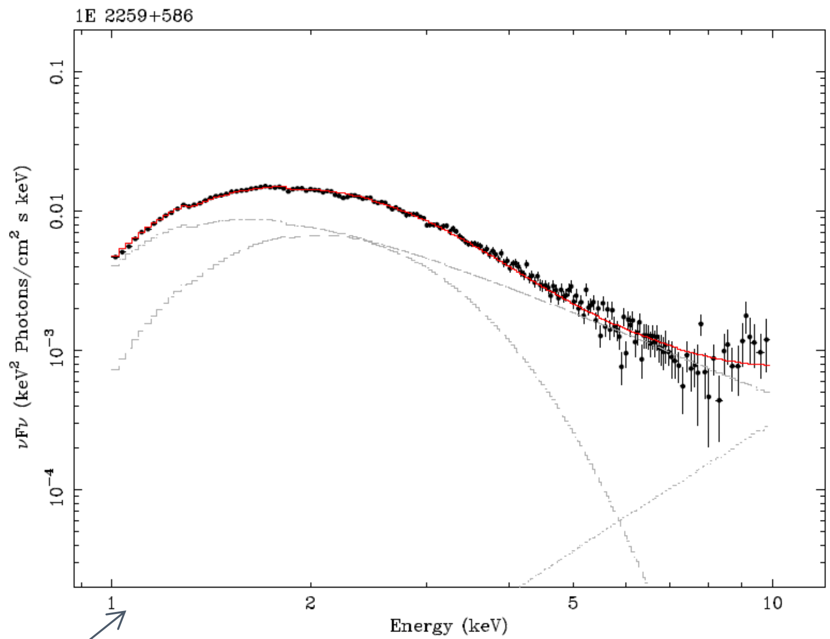
- $L_X > \dot{E}$ $\rightarrow$ not powered by rotation
- No evidence for a companion star $\rightarrow$ not powered by accretion
- Large measured spin-down rates
- Quite young objects ($\approx 10^3$ - 10^4 yrs): spin down to present periods (a few seconds) requires $B > 10^{14}$ G
- Giant flares energetics requires $B > 10^{15}$ G
- Opacity suppression for the X polarization mode in a strong B-field explains the large, super-Eddington flux in bursts

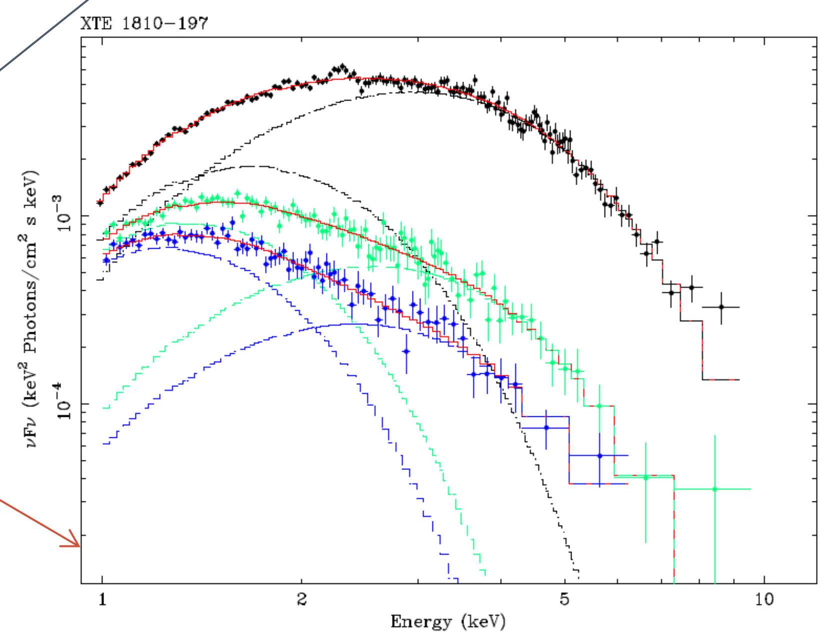
No direct measure of a super-strong field until recently

SGRs and AXPs X-ray Spectra

- 0.5 – 10 keV persistent emission well represented by a blackbody plus a power law
- $kT_{BB} \sim 0.5$ keV, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$, AXPs tend to be softer
- SGRs and AXPs are variable (months/years)
- Variability mostly associated with the non-thermal component
- Many transient sources visible only during outbursts ($L_X \approx 10 - 1000\ L_{quies}$)
- Transient spectra can be BB+BB, T_{BB} and R_{BB} decrease in time







SGR 1806-20 at different epochs (BB+PL)

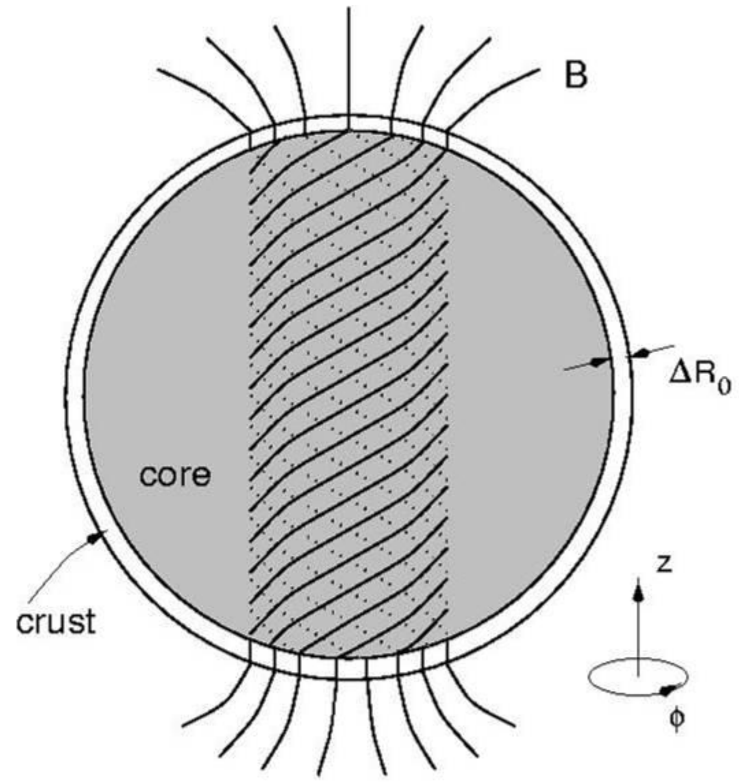
AXP 1E 2259-586 (BB+PL)

Transient AXP XTE 1810-197 at different epochs (BB+BB)

XMM Epic-pn data (Rea el al. 2008)

Twisted Magnetospheres – I

- The magnetic field inside a magnetar is "wound up"
- The presence of a toroidal component induces a rotation of the surface layers
- The crust tensile strength resists
- A gradual (quasi-plastic ?) deformation of the crust
- The external field twists up (Thompson, Lyutikov & Kulkarni 2002)

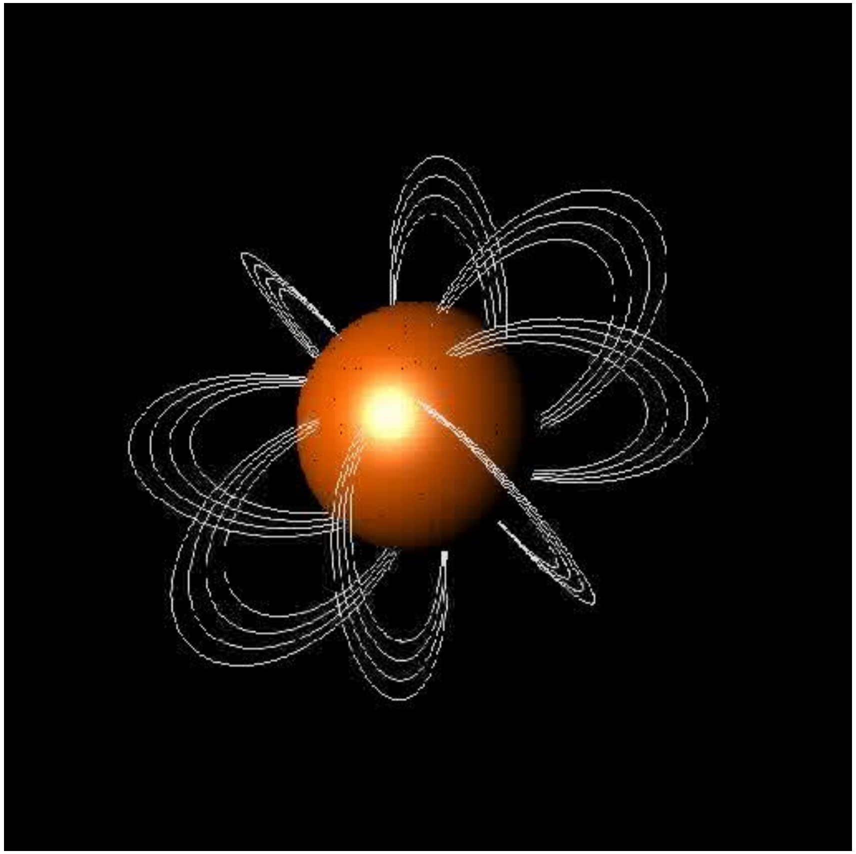


Thompson & Duncan (2001)

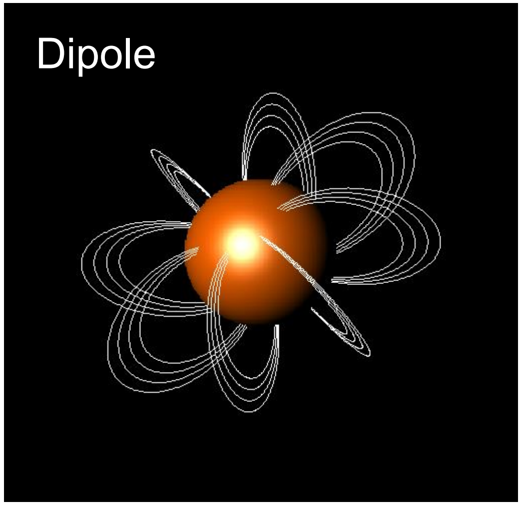
Twisted Magnetospheres - II

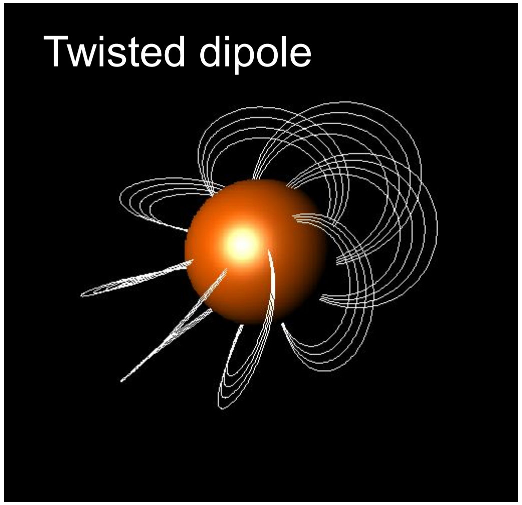
- Twisted fields are non-potential, $\nabla \times \vec{B} \neq 0$
- Globally twisted dipole (Thompson, Lyutikov & Kulkarni 2002, Pavan et al. 2009)
- A sequence of models labeled by the twist angle

$$\Delta\varphi_{N-S} = 2\int_0^{\frac{\pi}{2}} \frac{B_\varphi}{B_\theta}\frac{d\theta}{\sin\theta}$$



Magnetospheric Currents





$$\nabla \times \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{B} \neq 0$$

No need for supporting currents

$$\boldsymbol{j} = \frac{c}{4\pi} \nabla \times \boldsymbol{B}$$

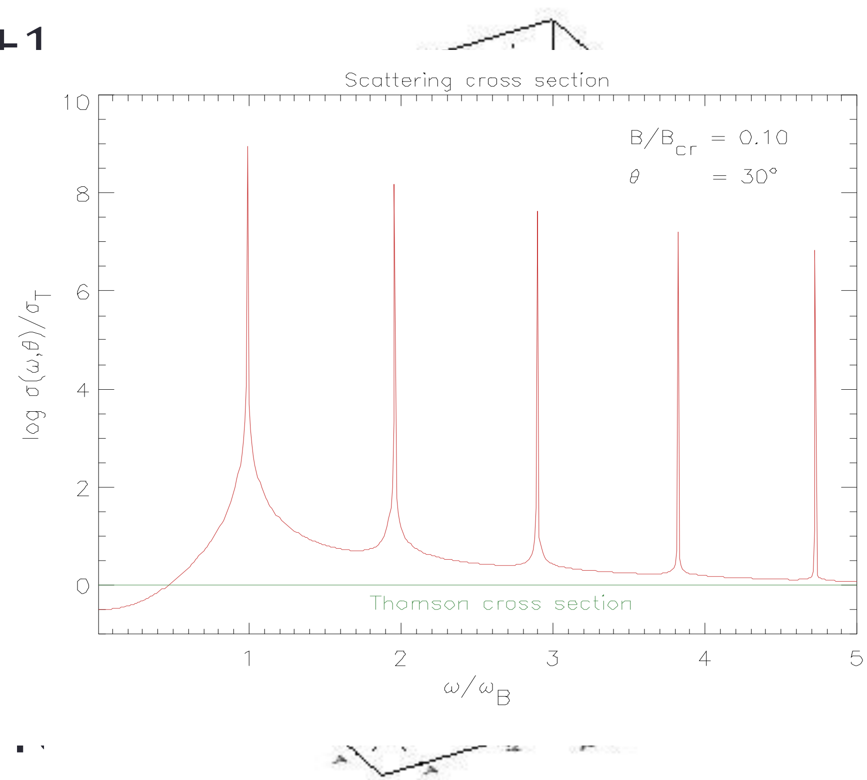
Currents flow (also) along the closed field lines and $j \gg j_{GJ}$

Resonant Compton Scattering

- The current flowing along the closed field lines is

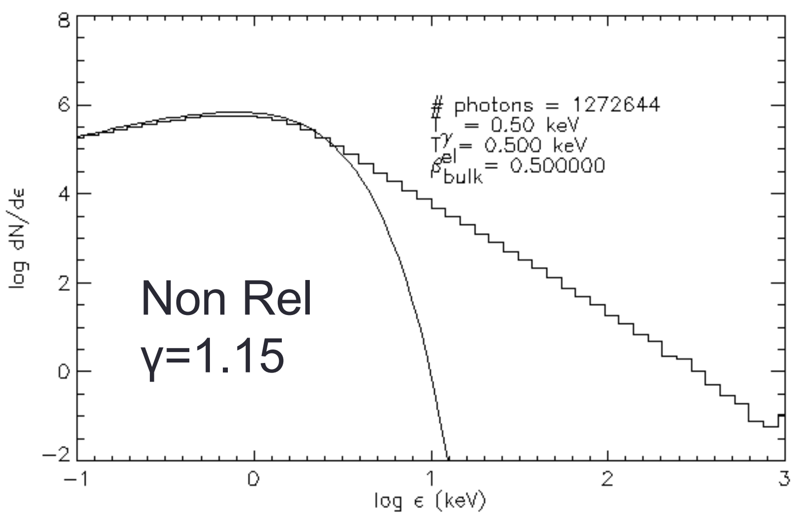
$$\boldsymbol{j} = \left(\frac{c}{4\pi}\right)\nabla \times \boldsymbol{B} \Rightarrow n_e = \frac{p+1}{4\ldots}$$

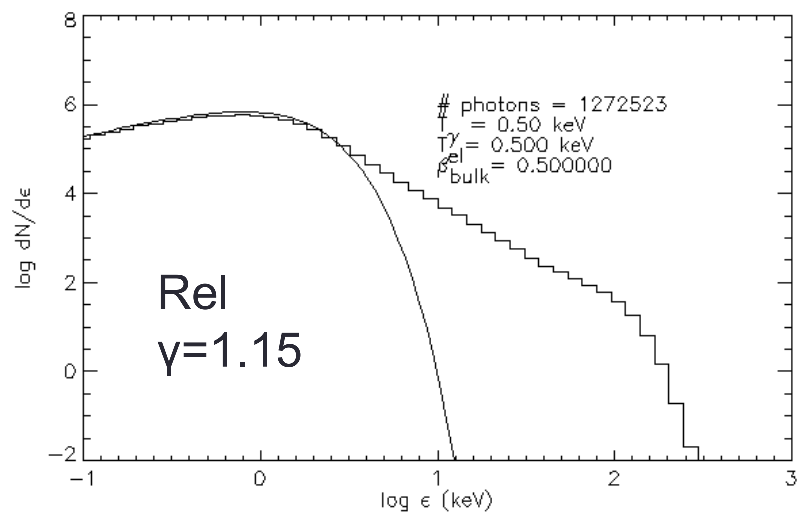
- The optical depth for Thom
$n_e \sigma_T r \approx 10^{-4}$
- At resonance $\sigma \approx 10^5\ \sigma_T \rightarrow$ resonant cyclotron scatteri
- Up-scattering of thermal pl cooling surface onto mildly . .

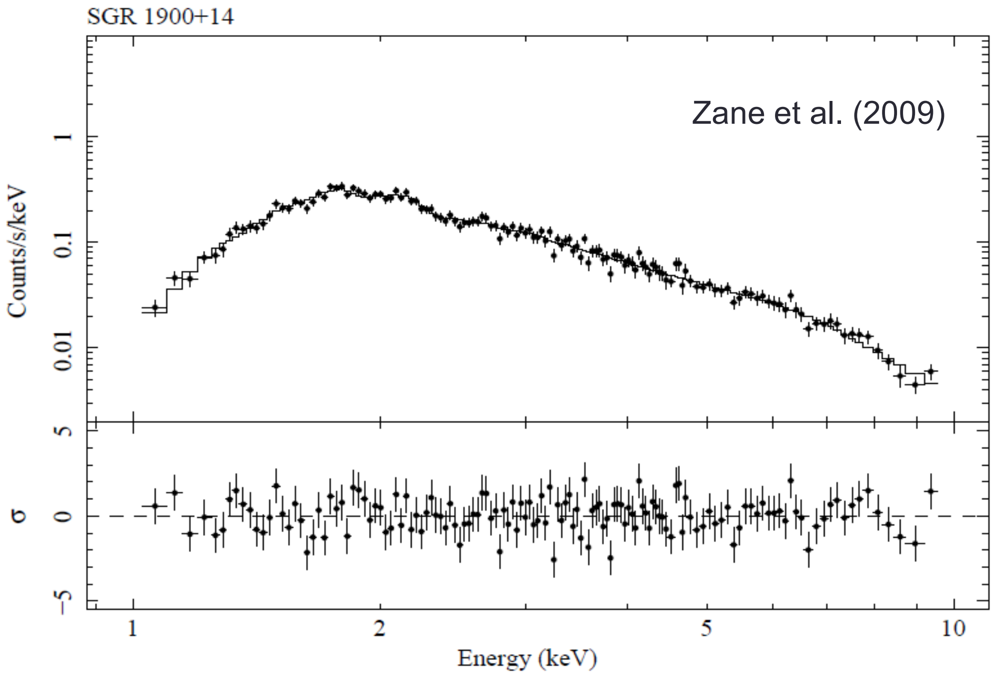


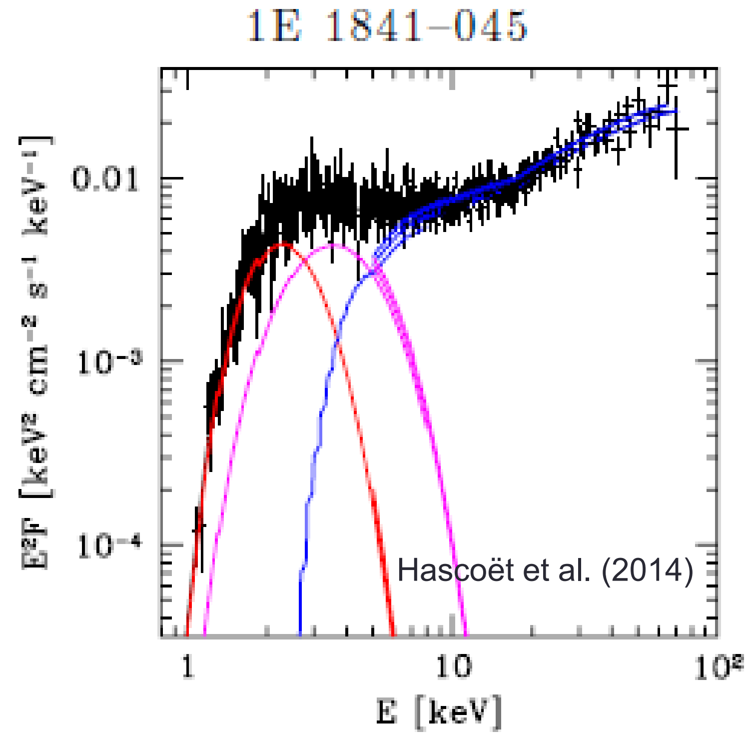
Repeated scatterings lead to the formation of a power-law tail because $\omega_D = \omega_D(r,\theta)$ and $r_{current} > R_{NS}$

Spectral formation in twisted magnetospheres investigated quite in detail using Montecarlo methods (Lyutikov & Gavriil 2006; Fernandez & Thompson 2007; Nobili, Turolla & Zane 2008a, b)









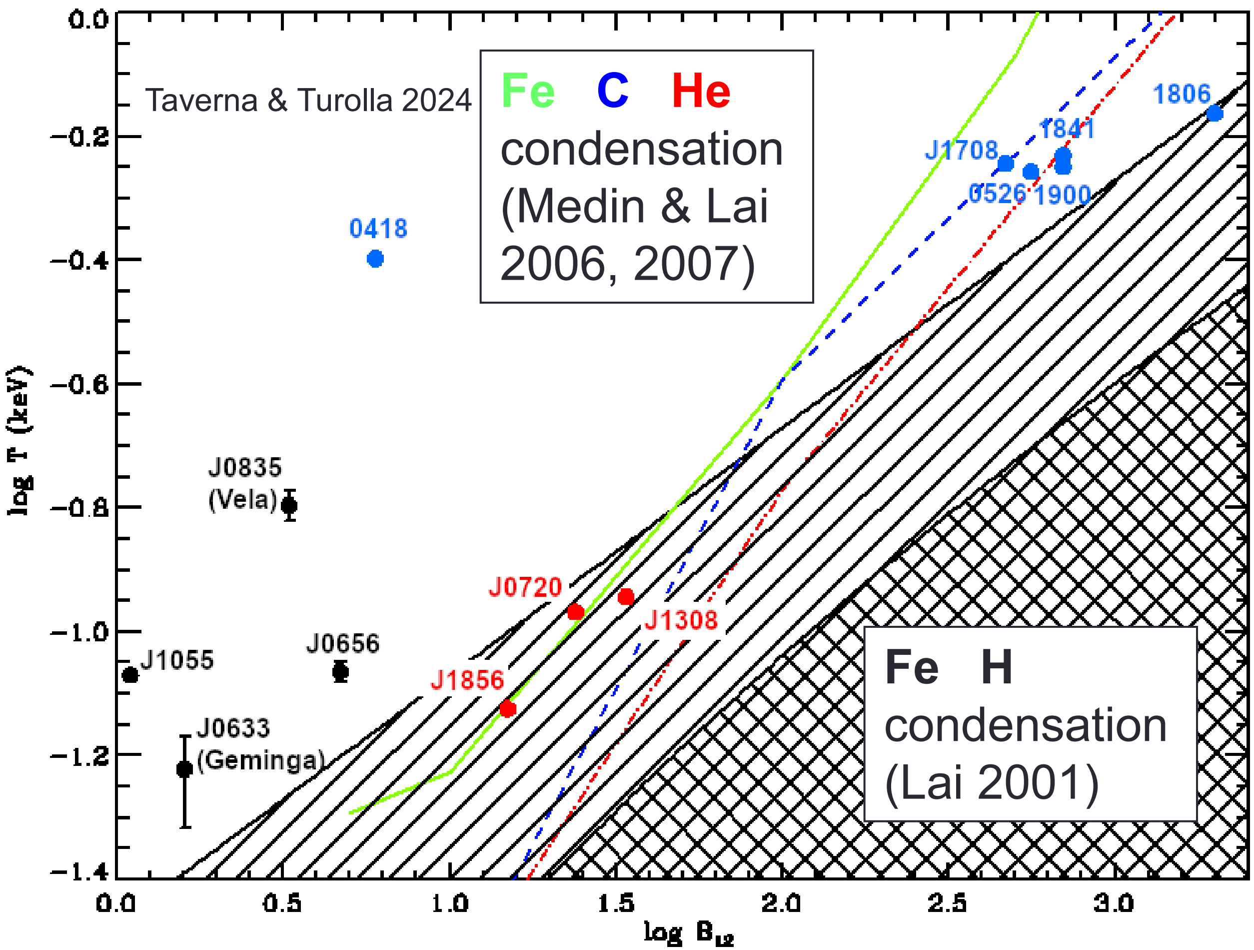
RCS models quite successful in explaining magnetars soft X-ray spectra (~ 0.5 – 10 keV) and also high-energy tails

Spectral fits provide information on the physical state of the star/magnetosphere (twist angle, charge velocity, surface temperature, etc)

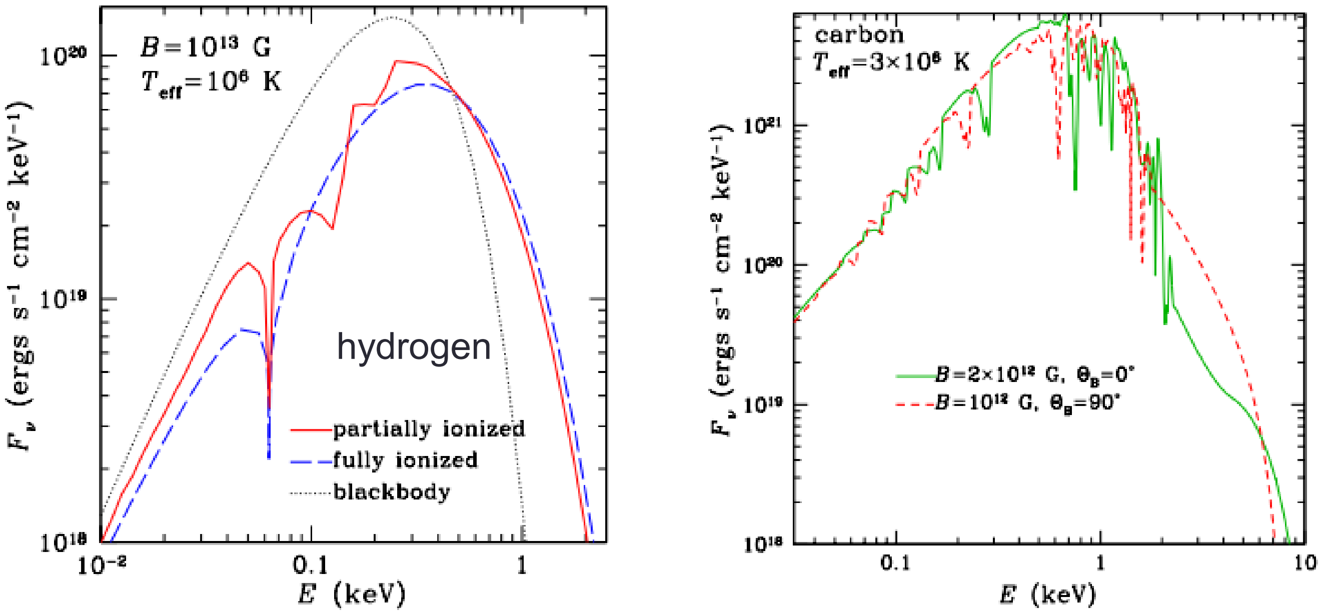
No single spectral model can consistently explain observations in the 0.5-100 keV band though

A “Hard” Surface ?

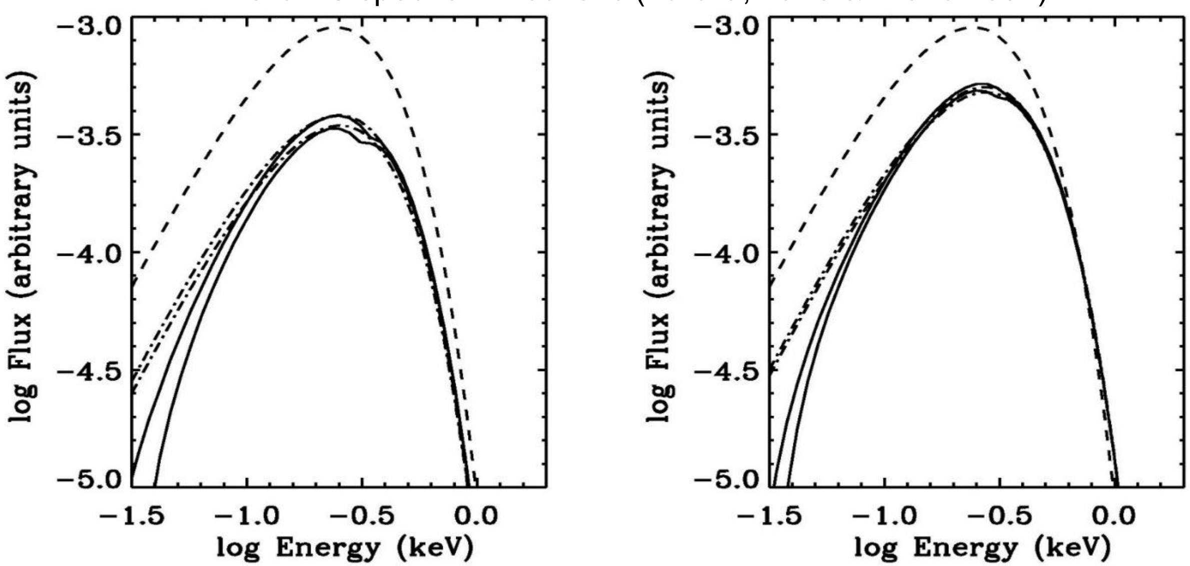
- NS … SM or fro… C, Ne, Fe)
- Un… eous sta
- Fo… field dire
- Fo… on co… tate: “ba
  V… itted



NS atmosphere spectra - (Ho 2008; Mori & Ho 2007)



Bare NS spectra - fixed ions (Turolla, Zane & Drake 2004)

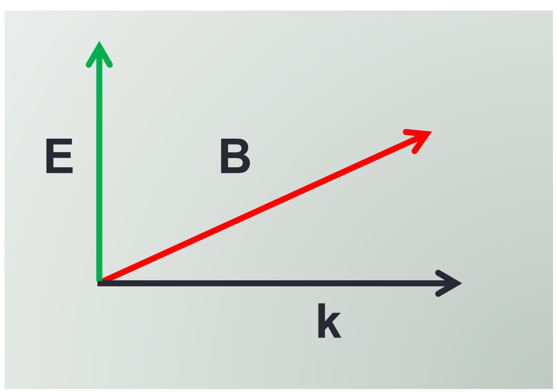


Spectra not too different

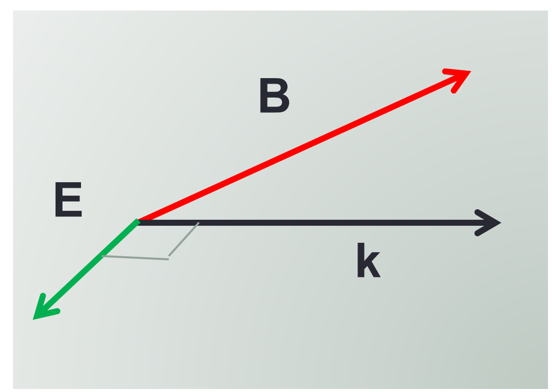
Matter and Radiation in Strong B-field

- A magnetized plasma/vacuum is anisotropic and birefringent, radiative processes sensitive to polarization state
- Two normal, linearly polarized modes in the magnetized medium: the extraordinary (X) and ordinary (O) mode
- Opacities greatly reduced for X-mode photons, $\kappa_O \sim \kappa_{unmag}, \kappa_X \sim (B/B_Q)^{-2}\, \kappa_{unmag}$

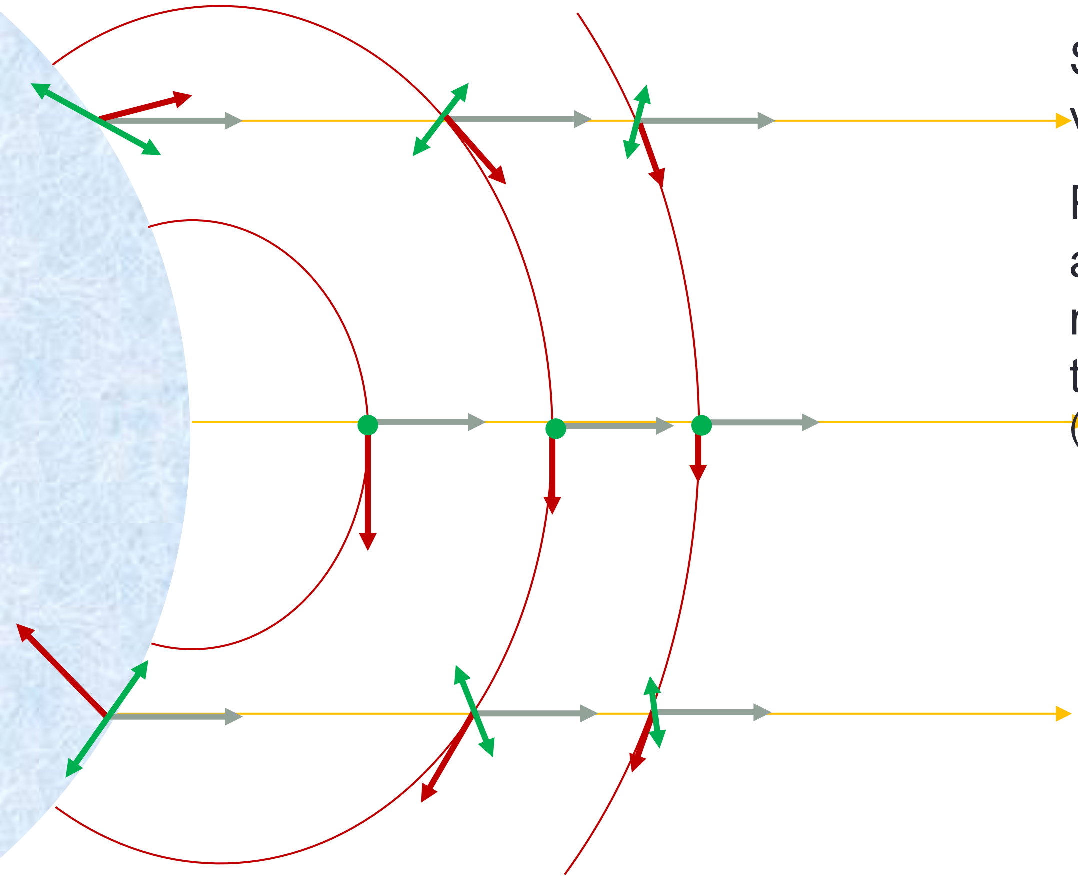
O mode



X mode

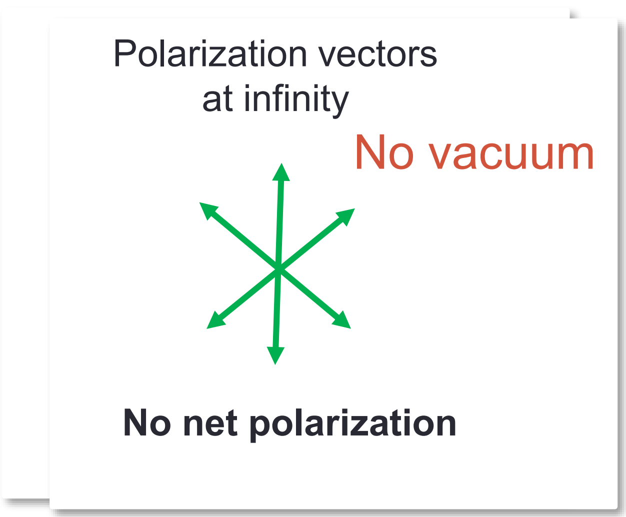


Propagation in Strongly Magnetized Vacuum



Strong magnetic fields polarize the virtual e^{-}-e^{+} pairs around the star

Polarization vectors are forced to adiabatically follow the star magnetic field along the photon trajectory
(Heyl & Shaviv 2000, 2002)

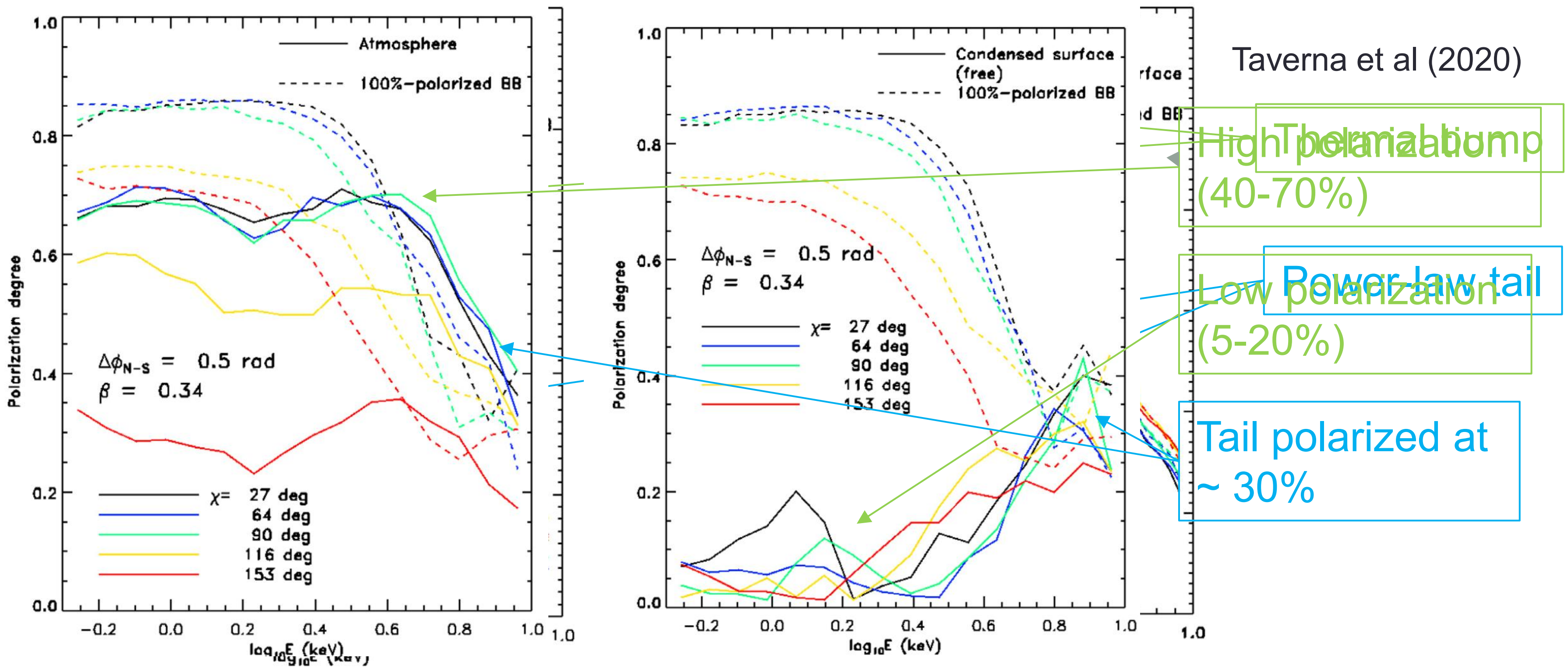


X-ray Polarization

- Thermal surface emission polarized in the X-mode
- Scatterings can change the photon polarization state
- The observed polarization fraction and polarization angle depend on QED effects ("vacuum polarization") and on magnetic field geometry (Stokes parameters rotation)
- Π_L and χ_p very sensitive to the source geometry (inclination of the LOS and of the magnetic axis wrt the rotation axis) AND on the state of the outermost layers
- X-ray polarimetry will provide an entirely new tool in magnetar studies

IXPE

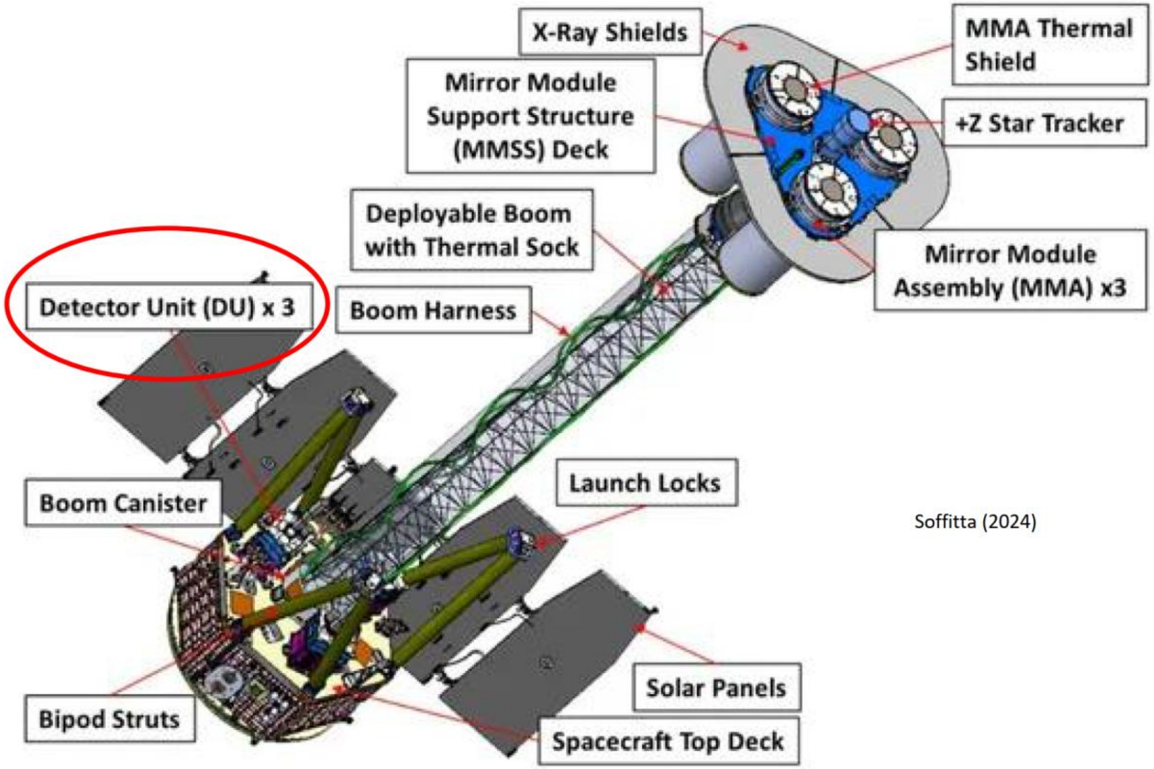
Magnetar Spectra vs. Polarization



Spectra are quite similar but polarization is not

- sensitive to the emission model
- sensitive to geometry

Imaging X-ray Polarimetry Explorer (IXPE)



Soffitta (2024)

A NASA/ASI SMEX mission

Three identical Mirror Module Assembly + Detector Units

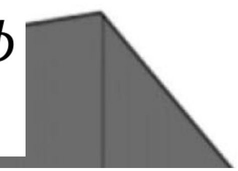
Launched on December 9, 2021

The Gas Pixel Detector

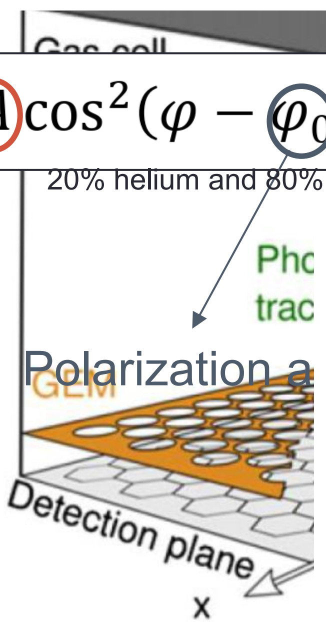
Photoelectric cross section

$$\frac{d\sigma_{\mathrm{Ph}}}{d\Omega} = r_0^2 \alpha^4 Z^5 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta}{(1-\beta\cos\theta)^4}\cos^2\phi$$

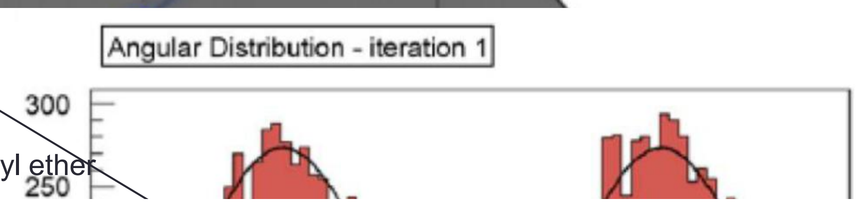
beryllium window



$$\mathcal{M}(\varphi) = K + A\cos^2(\varphi - \varphi_0)$$



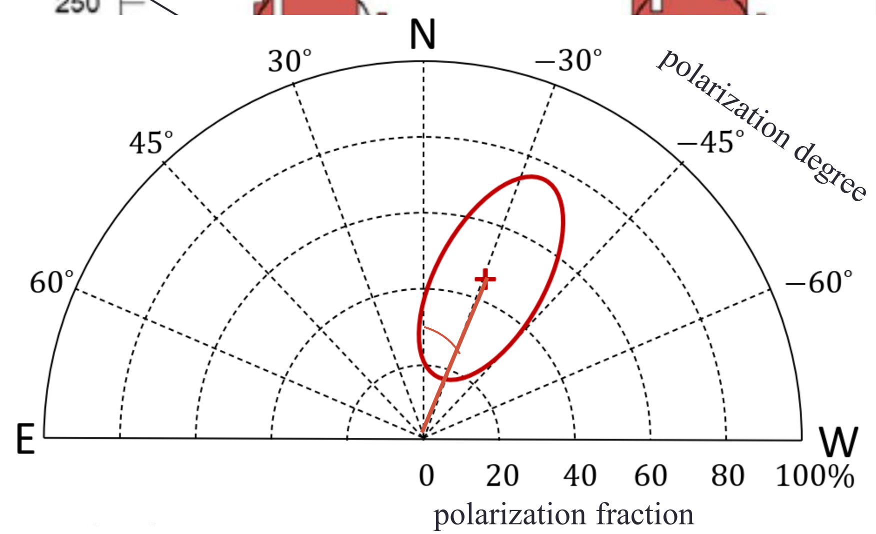
20% helium and 80% dimethyl ether



Polarization degree

Polarization a

polarization direction



Muleri (2014)

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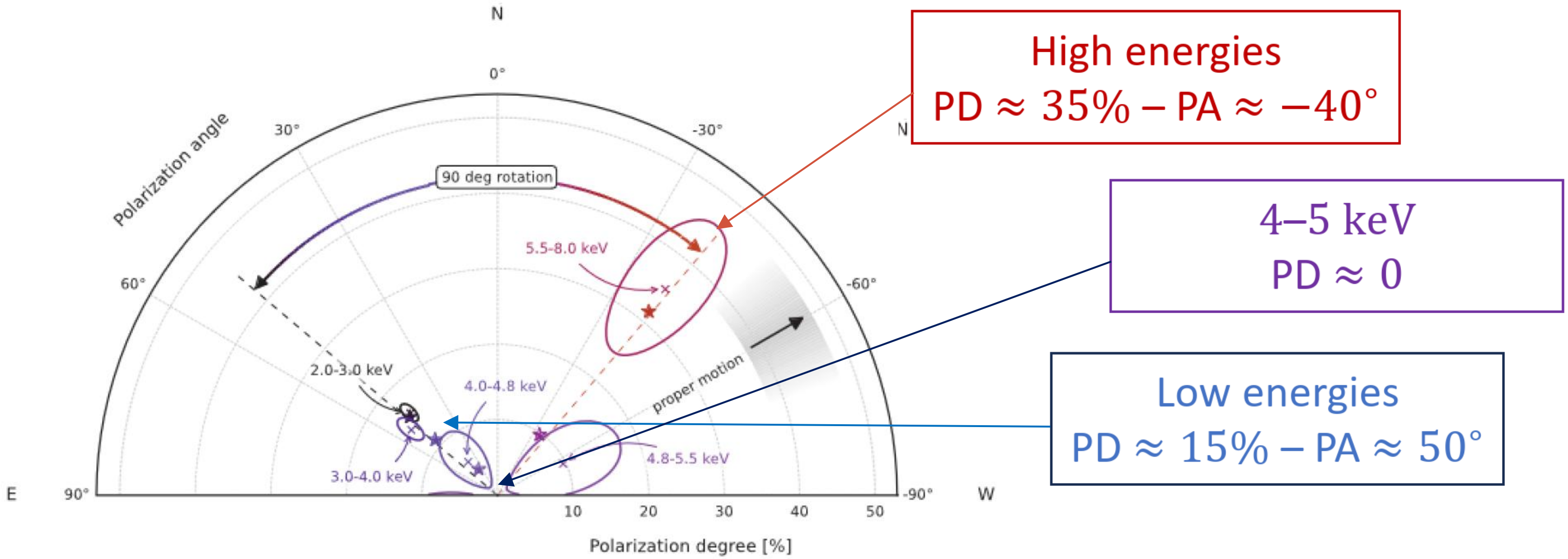
IXPE Observations of Magnetars

- AXP 4U 0142+61 (840 ks)
  - Cassiopeia – Distance: 3.6 kpc
  - Unabsorbed flux (2–10 keV): 6×10^{-11} erg cm^{-2} s^{-1}
- AXP 1RXS J170849.0–4009100 (837 ks)
  - Scorpio – Distance: 5-10 kpc
  - Unabsorbed flux (2–10 keV): 2.4×10^{-11} erg cm^{-2} s^{-1}
- AXP 1E 2259+586 (1.2 Ms)
  - Cassiopea – Distance: 3.2 kpc
  - Unabsorbed flux (2–10 keV): 1.4×10^{-11} erg cm^{-2} s^{-1}
- SGR 1806-20 (947 ks)
  - Sagittarius – Distance: 8.7 kpc
  - Unabsorbed flux (2–10 keV): 4×10^{-12} erg cm^{-2} s^{-1}

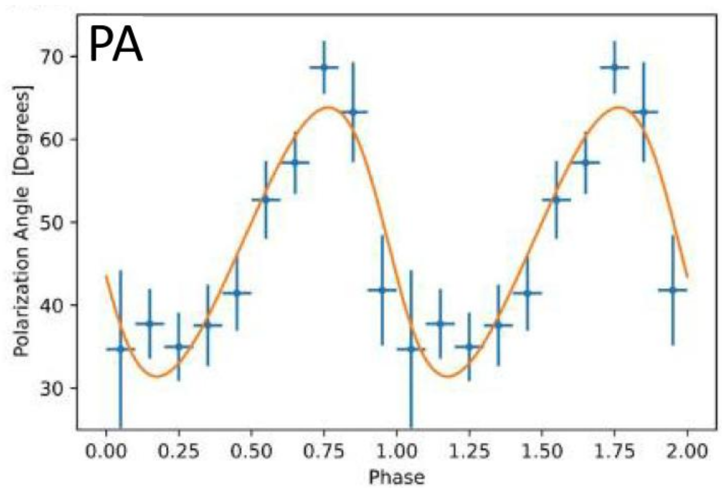
AXP 4U 0142+61 - I

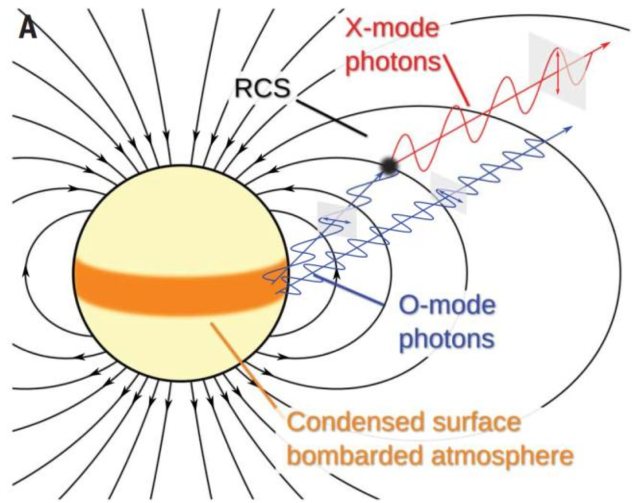
- Brightest magnetar
- Spin-down field B = 1.5×10^{14} G
- Spectrum BB+PL
- Polarization measurement (2–8 keV; Taverna et al. 2022):
  - PD = 13.5% (17σ), PA ≈ 50° E (energy- and phase-integrated)



Taverna et al. (2022)

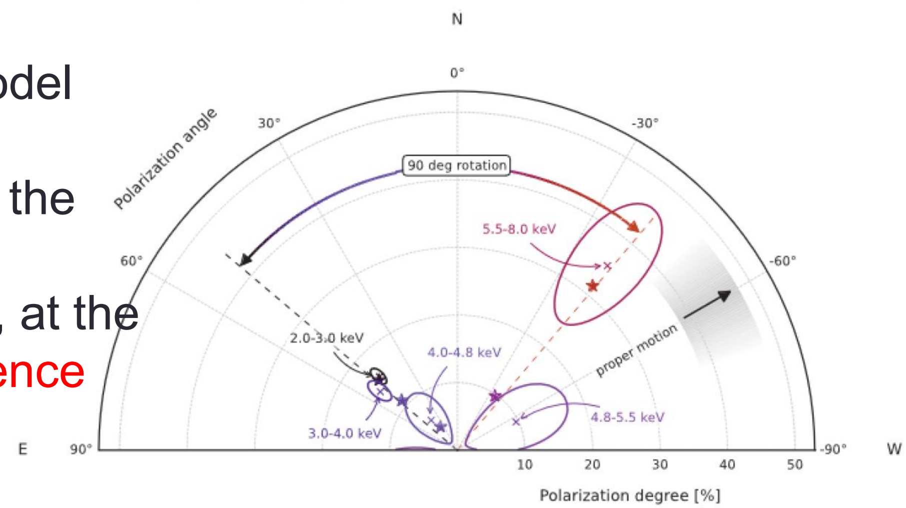
AXP 4U 0142+61 - II





- s photons
- RCS photons are X-mode → O-mode at low energies
- Low PD + O-mode photons → condensed surface

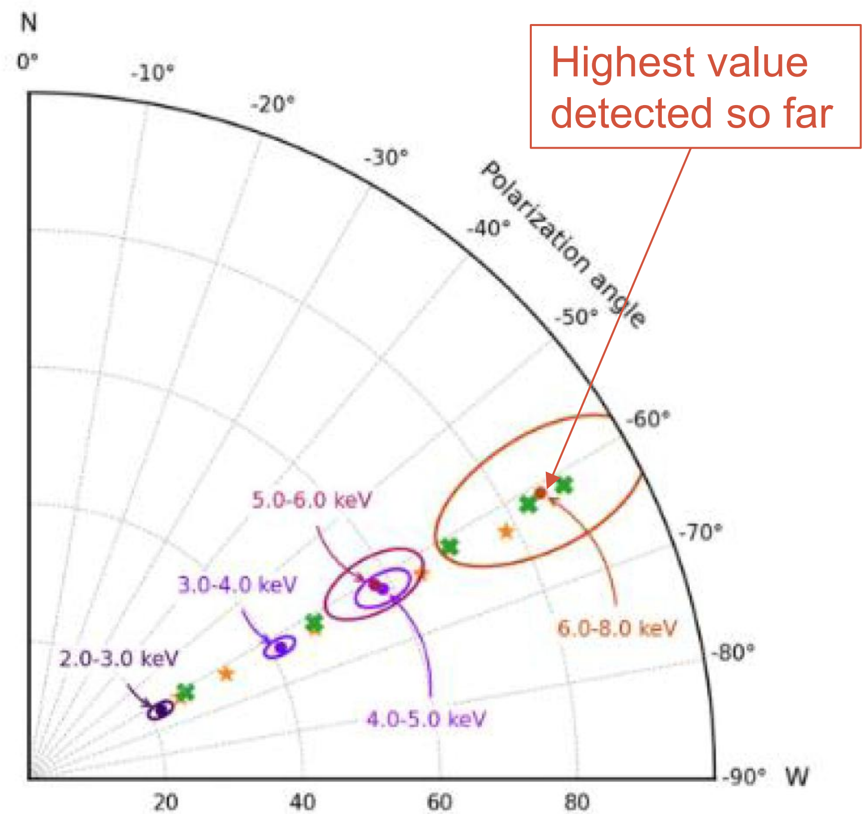
- Polarization angle well fit by RVM model
  - Shouldn't be like that !
  - RVM works only if B is constant over the emitting region
  - PA is fixed far away from the surface, at the adiabatic radius → vacuum birefringence



Taverna et al. (2022)

AXP 1RXS J1708 - I

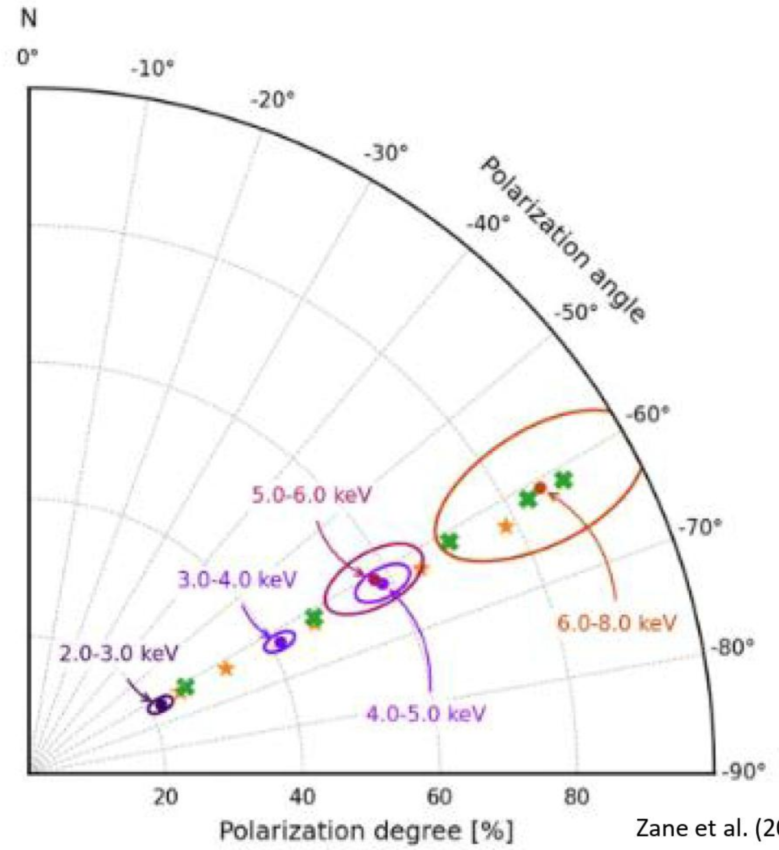
- Second brightest magnetar
- Spin-down field B = 5×10^{14} G
- Spectrum BB+PL or BB+BB
- Polarization measurement (2–8 keV; Zane et al. 2023):
  - PD = 35% (22σ), PA ≈ 60° W (energy- and phase-integrated)
  - PA constant with energy, PD increases over the IXPE band up to 80% at 6 – 8 keV



Zane et al. (2023)

AXP 1RXS J1708 - II

- PD at high energies too large for RCS (≈ 33%) → BB+BB (2 distinct thermal regions)
- High PD → NS atmosphere
- PD at low energies too small for atmosphere → condensed surface

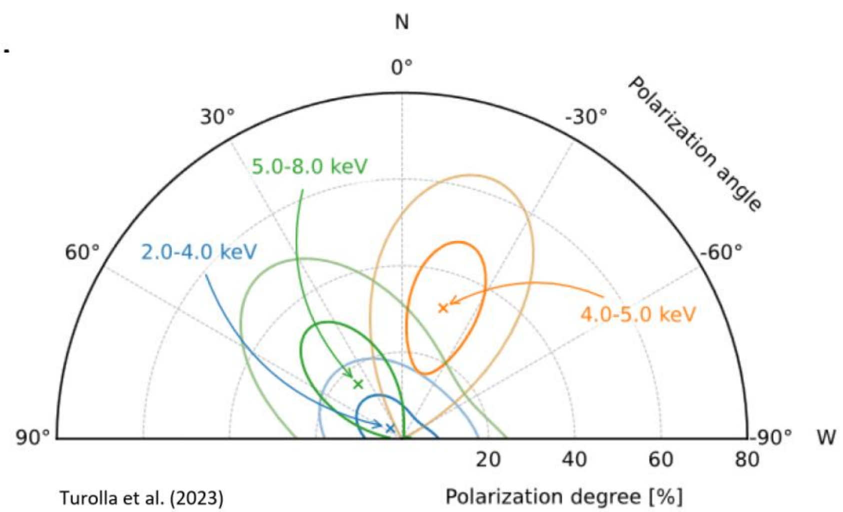


Zane et al. (2023)

Phase transition across the surface

SGR 1806-20

- Strongest field measured so far, B = 8×10^{14} G
- Emitted the most powerful giant flare in 2004, L ~ 10^{47} erg/s
- Spectrum BB+PL
- Flux at historical minimum, polarization marginally detected only in the 4 - 5 keV range (Turolla et al. 2023):
  - $\lesssim$ 24% (2–4 keV)
  - $\approx$ 32% (4–5 keV, 99% c.l.)
  - $\lesssim$ 55% (5–8 keV)



Turolla et al. (2023)

Compatible with being similar to 4U 0142+61

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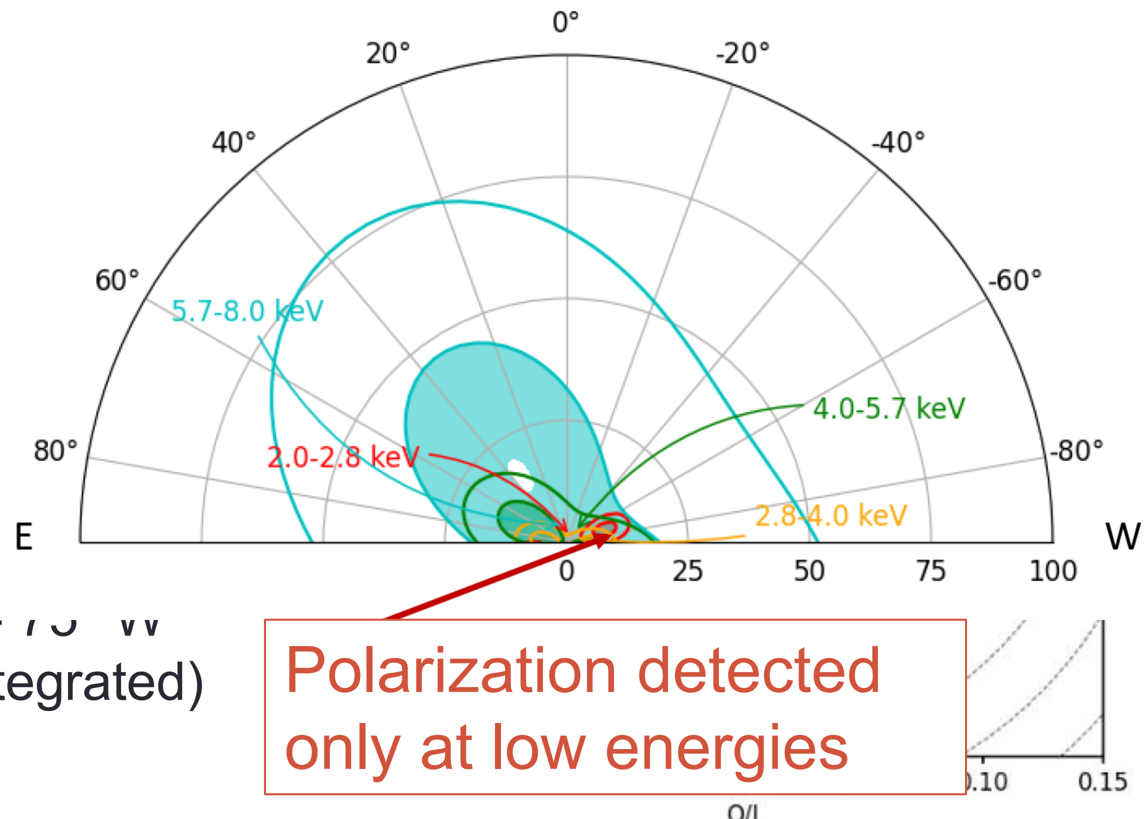
AXP 1E 2259+586 - I

- A Low-field magneta
  6x10^{13} G
- Spectrum BB+PL+a
  variable absorption f
  (Pizzocchero et al. 2
- Polarization measure
  (2–8 keV; Heyl et al.
  - PD = 5.6% (17σ), PA =
    (energy- and phase-integrated)



Heyl et al. (2024)

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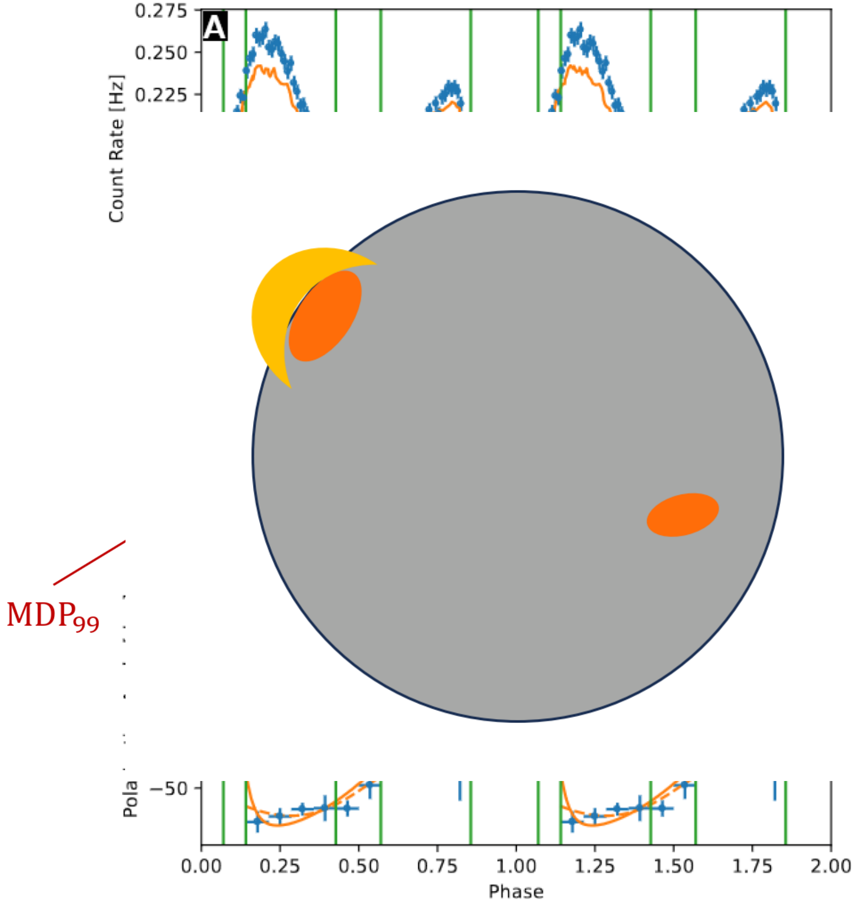
AXP 1E 2259+586 - II

- Polarization up to ~30% at particular phases (rise and maximum of the primary LC peak)
- Secondary peak basically unpolarized
- Fairly fitted by a RVM in which photons are assumed to change mode (from O- to X- and vice versa)

- Two emitting regions (condensed surface, O-mode dominated)
- One of the two spot covered by a magnetic loop with currents flowing along
- Primary photons reprocessed by RCS onto protons



Conclusions

- X-ray polarimetry ideally complements information from spectral and timing analysis
- Detection of photons polarized in two normal modes in the same source (4U 0142) confirms the presence of ultra-strong magnetic fields ($\gtrsim 5\times10^{13}$ G)
- Energy-dependent PD and PA conform to expectations of RCS model (when a PL is detected)
- Phase-dependent PD and PA provide a strong hint that vacuum birefringence is at work around magnetars
- Further magnetars should be explored in polarized X-rays (persistent and transient in outburst)