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Vacuum birefringence and X-ray polarimetry in transient magnetars

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Abstract. Recent optical polarimetry observations of an X-ray dim isolated neutron star, RX J1856.5−3754, showed a first evidence for QED vacuum birefringence induced by a strong magnetic field. This important result can be confirmed by performing systematically polarimetry observations in the X-ray band for other strongly magnetized neutron stars, such as transient or persistent magnetars. We computed the phase averaged polarization fraction (PF) and polarization angle (PA) expected in the thermal emission from transient magnetars in the soft X-ray energy band. We found that the detection of a PF higher than 60% is a strong evidence for vacuum birefringence. We also found that a steady change in the PA measured from transient magnetars during their outburst decay (up to 23 degrees for a magnetospheric untwisting of 0.5 rad) is a strong signature of vacuum birefringence. This latter detection would also provide an independent check of the magnetospheric untwisting model for these sources. Simulations show that these measurements are achievable by future polarimetric missions such as XIPE and IXPE with 20−380 ks of observational time, and with eXTP with 3−60 ks.

1. Introduction

According to quantum electrodynamics (QED), a strong magnetic field polarizes the vacuum, altering the dielectric and magnetic permeability tensors. This produces what is known as vacuum birefringence, predicted more than 80 years ago by Heisenberg and Euler (1936), that has been searched for in terrestrial laboratories but never detected. Neutron stars (NSs), with strong magnetic fields, are unique sources where we can study vacuum birefringence [1, 2, 3]. Recently, an optical polarimetry observation of an X-ray dim isolated neutron star (XDINS), RX J1856.5−3754 (hereafter RX J1856, with magnetic field $B \sim 10^{13}$ G), performed with the VLT, showed a phase-averaged polarization fraction, PF $\sim$ 16%, consistent with a potential signal of vacuum birefringence [4]. Future missions, such as the Imaging X-ray Polarimetry Explorer (IXPE [5]), the X-ray Imaging Polarimeter Explorer (XIPE [6]), and the enhanced X-ray Timing and Polarimetry mission (eXTP [7]), will allow us to perform X-ray polarimetry in transient magnetars (TMs, with magnetic fields $B \sim 10^{14}$ G). In these sources, the X-ray luminosity may increase up to ~ 3 orders of magnitude [8], providing the conditions for a further potential detection of vacuum birefringence. In this work, we model and study the polarization properties of TMs, extending our previous work on XDINSs [3].

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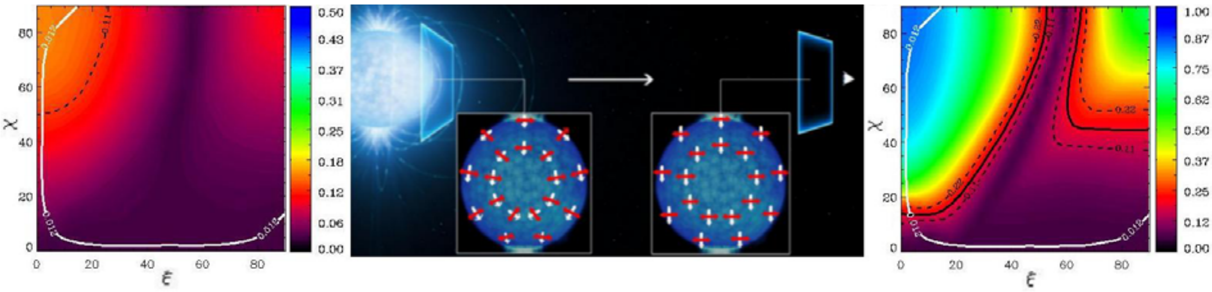

Figure 1. **Left Panel**: Phase-averaged PF for the radiation emitted from the NS surface (without vacuum birefringence) computed for different values of the angles ξ (magnetic axis and spin axis) and χ (line of sight and spin axis). The radiation is computed for a magnetized NS atmosphere, with $B \sim 10^{13}$ G as in the case of RX J1856, in the B-band for the VLT. The white line corresponds to the constraints on the viewing angles from the 1% X–ray pulsed fraction observed for RX J1856. Notice the [0.0–0.5] scale for the colorbar. **Central Panel**: Change of the electric field of the radiation as photons propagate through the NS magnetosphere. The subpanels show the direction of the photon E-field (red arrows) and the star B-field (white arrows) close to the surface (left subpanel) and after photons propagate through the magnetosphere with vacuum birefringence (right subpanel). Image credit: ESO. **Right Panel**: Same as in the left panel but accounting for vacuum birefringence. The black solid line corresponds to the PF observed with VLT and the black dashed lines mark the associated errors [4]. Notice the [0.0–1.0] scale for the colorbar.

2. XDINSs & Polarization Boost

Photons in a strong magnetic field are linearly polarized in two normal modes: the ordinary (O) and the extraordinary (X) modes, with the photon E-field oscillating either parallel or perpendicular to the plane of the local B-field and the photon propagation direction k. In a simplified picture, under vacuum birefringence, photons propagating in the NS magnetosphere rotate their electric field to re-adapt the normal modes according to the local direction of the magnetic field. This effect operates up to the so called adiabatic radius, which for XDINSs is located at a distance of a few NS radii [2]. As photons leave the star surface and travel along the line of sight (Figure 1, central panel), the magnetic field of the star becomes more uniform, which in turn forces a more uniform distribution of the electric field of the radiation, increasing the observed PF with respect to that produced according the B-field topology at the star surface [2, 3]. Figure 1 shows the PF expectations for RX J1856 in the optical band for **a)** the radiation emitted from the star surface, where the non-uniform B-field and the rotation of the Stokes parameters produce a relatively low PF (left panel), and **b)** the one obtained at the adiabatic radius (when vacuum birefringence is operating), where the B-field is more uniform and the small rotation of the Stokes parameters can produce a relatively high PF (right panel). If we consider vacuum birefringence (plus the constraints on the viewing angles given by the $\sim 1\%$ X-ray pulsed fraction and those discussed in [9]), the results of our simulations for different emission models (atmosphere, condensed surface and 100% polarized blackbody radiation) turn out to be in agreement with the observed PF$\sim 16\%$. If vacuum birefringence is neglected, the measured PF and the constraints on the viewing angles discussed in [9] cannot be reproduced. Therefore, this suggests a first detection of the signal of vacuum birefringence [4].

3. Transient Magnetars

TMs are relatively hot NSs with outburst activity in which their X-ray flux can increase up to 3 orders of magnitude within hours and then decay on a time-scale of months [8]. The outbursts

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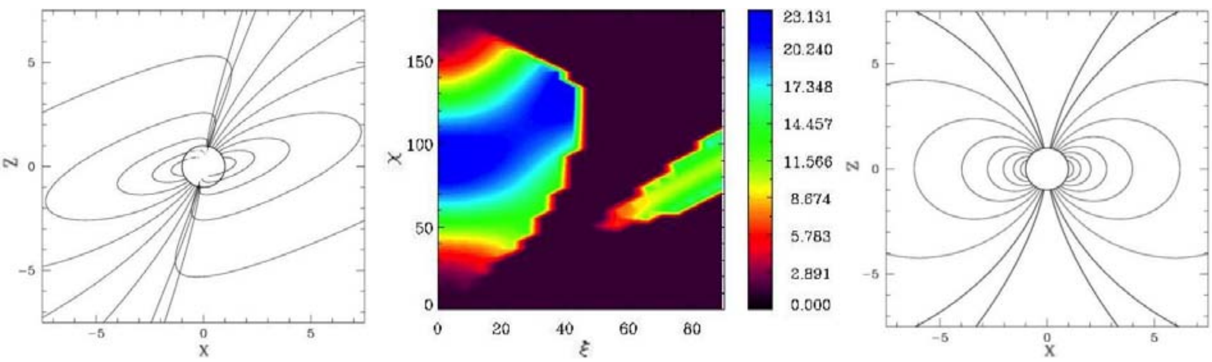

Figure 2. **Left Panel**: Example of a globally twisted magnetosphere with $\Delta\Phi = 2$ rad. **Central Panel**: Expected variation of the phase-averaged PA for TMs during a magnetospheric untwisting of 0.5 rad (as expected during the outburst decay, for details see Sec. 3), in the $2-6$ keV energy range. **Right Panel**: A fully untwisted magnetosphere, i.e. a perfect dipole. © The left and right panels are reproduced by permission of the AAS from the original ref. [10].

and subsequent flux decay observed in these sources are explained in the magnetar model in terms of catastrophic instabilities leading to a reconfiguration of the magnetosphere [10]. In particular, the internal toroidal field may transfer some helicity to the external magnetic field via plastic deformations or starquakes of the solid NS crust, producing a twisted magnetosphere (Figure 2, left panel). This twisted field evolves and gradually untwists [11, 12], dissipating magnetic energy until, eventually, a nearly dipolar, stable configuration is reached (Figure 2, right panel).

We model the polarization properties of TMs and study the phase-averaged PF and PA during the TM flux decay. For the TM mass and radius we assume canonical values $M = 1.5M_\odot$ and $R = 12$ km, respectively. Based on observational studies of representative sources such as XTE J1810−197 and CXOU J164710.2−455216 [13], we consider a TM with one hot polar cap, located in one of the magnetic poles, covering 15% of the star surface. Following [13], and for simplicity, we assume that the TM has a globally twisted magnetosphere. We assume that, at the flux peak, the magnetosphere has a twist angle $\Delta\Phi = 1.0$ rad and the hot polar cap has a uniform temperature of $T = 1.0$ keV. When quiescence is reached, the magnetosphere has untwisted by $\Delta\Phi = 0.5$ rad and the polar cap cooled down to $T = 0.5$ keV. These values are reminiscent of those inferred by [13], while analyzing the outburst decay of XTE J1810−197 and CXOU J164710.2−455216. We also assume that the X–ray thermal radiation is produced in a magnetized atmosphere composed of fully-ionized hydrogen. The intensities for the O-mode and X-mode are obtained by solving the radiative transfer equation, and assuming a polar magnetic field $B_p = 10^{14}$ G, perpendicular to the surface. These intensities are, then, used to model the thermal emission from the hot polar cap, neglecting the variation of the magnetic field over the relatively small extension of the emitting region. For computing the polarization quantities, we follow the procedure previously discussed for XDINSs [3], in which the Stokes parameters are computed at the adiabatic radius [2].

The results of our simulations can be summarized as follows: **a)** Similar to previous results obtained for XDINSs [3], the super-strong magnetic field surrounding TM can boost the observed PF of the thermal radiation, via the effect of vacuum birefringence, up to $\sim 99\%$ (considering the most favourable viewing geometry $\chi \sim 90°$ and $\xi \sim 0°$). **b)** When vacuum birefringence is operating and the TM has an untwisting magnetosphere, the value of PA can change up to 23 degrees (from the onset until quiescence, Figure 2, central panel), offering an interesting test for the magnetar model. **c)** If vacuum birefringence is not present and the polar cap shrinks during

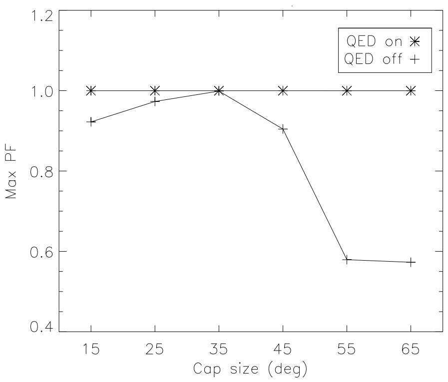

Figure 3. Maximum phase-averaged PF for different sizes of the polar cap (semi-angle of the polar cap). The line with asterisks symbols (*) corresponds to the case in which vacuum birefringence is operating. The line with crosses symbols (+) shows the case in which vacuum birefringence is not present. The radiation at the star surface is computed for a magnetized, pure-H atmosphere with $B_p = 10^{14}$ G and temperature $T = 0.5$ keV.

the TM flux decay, we found that the PF may increase from $\sim 65\%$ up to $\sim 99\%$ (Figure 3). Instead, if vacuum birefringence is operating, the PF stays almost constant independently on the cap size. This is an interesting result as it represents a further test on the magnetar scenario for TMs and the detection of a nearly constant PF as the decay proceeds will provide a further evidence for the presence of vacuum birefringence.

4. Future X-ray polarimetry missions

A number of missions devoted to X-ray polarimetry are currently under development, all with an estimated launch in the next decade: IXPE (NASA), XIPE (ESA), and eXTP (CAS/CNAS). All of them will be able to observe in 2−6 keV energy range, relevant for the study of TMs. Simulations (based on parameters for XTE J1810−197 and CXOU J164710.2−455216 [14, 15]) show that in order to observe a PF$\sim 70\%$ and variation of the PA~ 10 deg, at the onset of the outburst (with a maximum flux $\sim 10^{-11}$ erg/cm^2/s), the observation time required by eXTP and XIPE are ~ 3 ks and ~ 20 ks, respectively. At the end of the X-ray flux decay, when the TM is in quiescence (minimum flux $\sim 5 \times 10^{-13}$ erg/cm^2/s), the observation time required to detect the same PF and PA by eXTP and XIPE are ~ 60 ks and ~ 380 ks, respectively. IXPE has a similar sensitivity of XIPE, therefore the requested observing time is of the same order. IXPE will likely allow to detect 1-2 TM during the planned mission lifetime.

Acknowledgments

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