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Polarized X-rays from magnetar sources

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The study of the X-ray persistent emission from magnetars offers an unprecedented opportunity to gain insight into the physical processes that occur in the presence of ultra-strong magnetic fields. Up to now, most of our knowledge about magnetar sources came from spectral analysis, which allowed us to test the resonant Compton scattering (RCS) scenario and to probe the structure of the star magnetosphere. Due to the huge magnetic fields, radiation emitted from the magnetar surface is expected to be strongly polarized, and its observed polarization pattern bears the imprint of the physical mechanisms that occur on the surface of the star, RCS onto magnetospheric charges and quantum electro-dynamics (QED) effects as photons propagate in the magnetized vacuum (the vacuum birefringence). In this work we present and discuss the X-ray polarization detection in three magnetar sources by the Imaging X-ray Polarimetry Explorer (IXPE), comparing them with numerical predictions given by state-of-art theoretical models.

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1. Introduction

Magnetars are a particular class of isolated neutron stars (NSs), observationally identified as anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) which share some common properties (see [1–2] for reviews):

- they exhibit large spin periods ($P \approx 1$–12 s) and spin-down rates ($\dot{P} \approx 10^{-14}$–$10^{-10}\ \mathrm{s\,s^{-1}}$), which lead to infer ultra-strong dipolar magnetic fields ($B \approx 10^{14}$–10^{15} G);
- their persistent X-ray luminosity ($L_{\mathrm{X}} \approx 10^{33}$–$10^{35}\ \mathrm{erg\,s^{-1}}$) is normally in excess of the rotational energy loss rate (so they cannot be powered by rotation, but the energy of their huge internal magnetic field should play an important role);
- they are characterized by the emission of short bursts/intermediate-giant flares, with durations ranging from few tenth to hundreds of seconds, in which the emitted luminosity is strongly enhanced (from 10^{36} to $10^{47}\ \mathrm{erg\,s^{-1}}$);
- the persistent spectra in the soft X-ray band (0.5–10 keV) is usually fitted by the superposition of a thermal (blackbody, BB) component and a power-law (PL) tail (with many sources showing an additional PL component above 20 keV).

The Imaging X-ray Polarimetry Explorer (IXPE, [3]) mission observed the X-rays from three magnetar sources, opening a new window in the study of the physics and phenomenology of these sources. In this work we will illustrate the results of these observations and provide a proper model interpretation in the framework of the most commonly-accepted theoretical models.

2. Theoretical framework

2.1 Twisted-magnetosphere model

The most successful theoretical model so far in explaining the phenomenology observed for magnetar sources is the so-called twisted magnetosphere model [4]. According to this, the external magnetic field of magnetars is twisted, i.e., it is endowed with a non-negligible toroidal component, transferred from the highly wound-up internal magnetic field. Such a magnetic field is non potential, so that currents must flow along the closed magnetic field lines. The density of these charged particles (typically electrons and positrons) in the magnetosphere is too low to make Compton scattering with surface-emitted photons effective. However, the cross section can increase remarkably for photons at the particle cyclotron energy. As a result, thermal photons coming from the surface are expected to be up-scattered in the magnetosphere via resonant Compton scattering (RCS). This can explain the twofold nature of magnetar soft X-ray spectra, with the thermal component ascribed to the photons arriving at infinity directly from the surface and the PL tail caused by those reprocessed in the star magnetosphere.

2.2 Polarization properties of X-rays in strong magnetic fields

In the presence of strong magnetic fields (like those which are believed to be present around magnetars), photons at X-ray energies are expected to be linearly polarized in two normal modes, namely the ordinary (O) and the extraordinary (X) modes, with the photon electric field oscillating either parallel or perpendicular, respectively, to the plane made by the photon propagation direction and the star magnetic field. Despite this, the polarization degree observed at infinity may be much lower than what is expected at the emission. This is because the direction of the magnetic field in a neutron star (especially close to the surface) changes, in general, from point to point across the emission region. Hence, even assuming that all the emitted photons are polarized in the same mode, if the emitting region is sufficiently large the photon polarization vectors are expected to point in different directions, resulting in a low (or null) polarization degree.

Nevertheless, radiation from magnetars is anyway expected to be highly polarized thanks to vacuum birefringence, a quantum electrodynamics (QED) effect which takes place in strong magnetic fields, first theorized by [5], but never tested as yet in Earth laboratories. According to this, strong magnetic fields (typically of the order or in excess of the quantum critical field limit $B_Q \approx 4.4 \times 10^{13}$ G) are able to polarize the virtual electron-positron pairs that fill the vacuum around the neutron star, making it birefringent (i.e., O- and X-mode photons propagate with slightly different refractive indices through the magnetized vacuum). It can be shown [6–9] that, due to this effect, the orientation of the photon electric field with respect to the star magnetic field is kept fixed to the original one up to a distance from the star

$$r_{\rm pl} \simeq 5 \left(\frac{E}{1\ \mathrm{keV}}\right)^{1/5} \left(\frac{B_{\rm p}}{10^{11}\ \mathrm{G}}\right)^{2/5} \left(\frac{R_{\rm NS}}{10\ \mathrm{km}}\right)^{1/5} R_{\rm NS}\,,$$

where E is the photon energy, $B_{\rm p}$ the magnetic field strength at the pole and $R_{\rm NS}$ the stellar radius. At such a distance the magnetic field strength has decayed enough, and the magnetic field topology is expected to be much more uniform than at the surface, so that also the photon polarization vectors are oriented along nearly the same direction. As a consequence, one should measure a net polarization degree at infinity, even as high as the intrinsic one, determined by the emission processes which occur at the emission region.

2.3 Spectral and polarization properties at the emission region

In order to interpret theoretically the IXPE observations, we consider essentially two emission models. In the first one, surface radiation is reprocessed in a standard, cooling and magnetized atmosphere lying just above the surface (see [10]): here, radiative processes (mainly bremsstrahlung and Compton scattering) in the strong field limit are accounted for, together with full mode conversion at the vacuum resonance according to the model presented by [11] (see also [12]). In the second one, magnetic condensation is accounted for. In strong magnetic fields and for sufficiently low temperatures, atoms are elongated along the magnetic field direction, forming molecular chains via covalent bonding. In this way, the atmosphere can condense, precipitating on the star surface and leaving exposed the stellar solid surface [13–15].

These two models are not much different from the spectral point of view, both predicting blackbody-like spectra, except for some features (like cyclotron lines, atomic transitions etc.) which can be present in the atmospheric case (see Fig. 1). What is really different between the two models is the polarization spectrum (see Fig. 2): in the atmosphere case we expect a very high polarization degree, more than 80% at all X-ray energies, with radiation overall polarized in the extraordinary mode; in the solid-surface case, the expected polarization degree is much lower (not exceeding 20%), and both ordinary and extraordinary photons may be detected in the collected radiation, according to the geometry of view under which the source is observed.

The possible reprocessing of photons in the magnetosphere through RCS should also be taken into account. In this case, as well as raising the power-law tail in the soft X-ray spectrum,

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also the polarization properties can be modified. In fact, looking at the RCS cross sections (see [16]) one can conclude that:

$$\sigma_{\mathrm{OO}} = \sigma_{\mathrm{OX}}/3$$
$$\sigma_{\mathrm{XX}} = 3\sigma_{\mathrm{XO}}\,,$$

i.e. photons have a larger probability to emerge from the magnetosphere in the extraordinary mode than in the ordinary one. Hence, a polarization degree $\sim 33\%$ can be expected at high energies, where the PL component dominates in the spectrum, regardless of the original emission model.

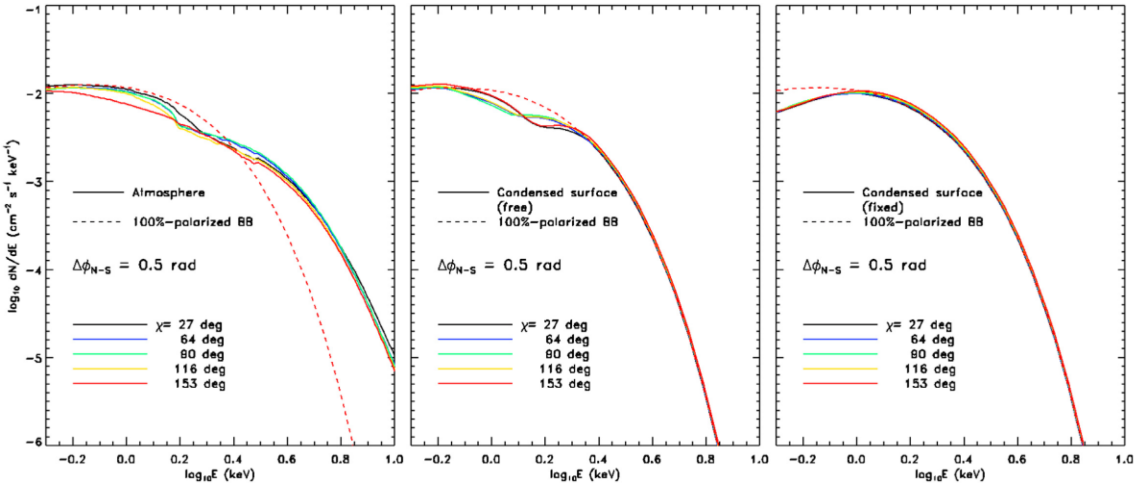

Figure 1: Surface X-ray spectrum simulated for the surface emission of a magnetar with a globally-twisted (twist angle $\Delta\phi_{\mathrm{N-S}} = 0.5$ rad) dipole magnetic field with polar strength $B_{\mathrm{P}} = 5 \times 10^{14}$ G and a constant surface temperature of $kT = 0.5$ keV, in the case of the atmosphere model (left) and condensed surface model in the free-ions (center) and fixed-ions (right) limits (see [14]). The magnetic dipole axis is aligned with the star rotation axis, while the different colored curves show the expectations for different inclinations χ of the observer's line-of-sight with respect to the star spin axis. In all the panels the blackbody distribution at the temperature kT is shown for comparison (red-dashed line). Image taken from [15].

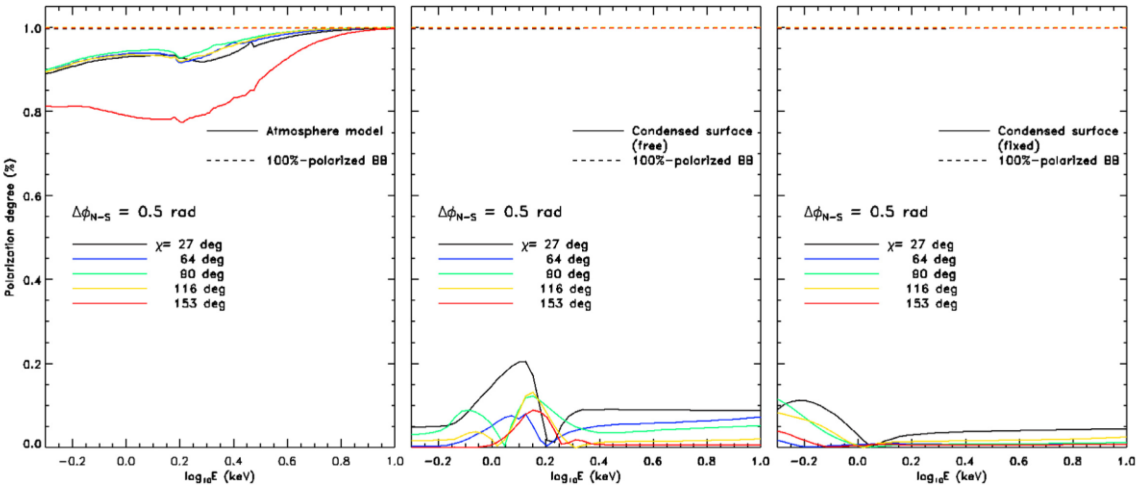

Figure 2: Same as in Fig. 1 but for the polarization degree as a function of the photon energy (taken from [15]).

3. IXPE observations

Here we discuss in detail the IXPE observations of three magnetar sources: the AXPs 4U 0142+61 and 1RXS J170849.0–4008, and the SGR 1806–20.

3.1 4U 0142+61

The AXP 4U 0142+61 is located in the Cassiopeia constellation, at an estimated distance of around 3.6 kpc, and it is the brightest among the magnetar sources, with a persistent unabsorbed flux $\sim 6 \times 10^{-11}$ erg cm^{-2} s^{-1} in the 2–10 keV band [17]. IXPE observed this magnetar between January 31st and February 27th, 2023, for a total exposure time of ~ 840 ks [18]. We performed a timing analysis in the IXPE working energy band 2–8 keV, extracting a double-peaked profile, with a pulsed-fraction $\sim 15\%$, spin period $P \approx 8.69$ s and spin-down rate $\dot{P} \approx 1.59 \times 10^{-12}$ s s^{-1}. From these values we could infer a magnetic field intensity for spin-down $B_{\rm sd} \approx 1.5 \times 10^{14}$ G, which is in agreement with previous observations, and it is high enough to observe high magnetic field effects in the polarization signal.

Since IXPE can only observe above 2 keV, it is not possible to constrain interstellar absorption using the IXPE data only. However, freezing the column density $N_{\rm H}$ to the value reported in the literature for the most recent observations of the source [19], we found that fitting the IXPE spectrum with the traditional BB+PL decomposition results in an acceptable agreement ($\chi^2 = 512$ for 411 degrees of freedom, dof). In this case we found values of the fitting parameters ($kT_{BB} = 0.471 \pm 0.004$ keV and PL spectral index $\Gamma = 3.69 \pm 0.05$) which are compatible with those reported by previous works [17, 19]. On the other hand, we checked that also a purely thermal decomposition, with two blackbody components, can explain well the spectral shape ($\chi^2 = 496$ for 411 dof), with reasonable spectral parameters (see [18] for more details).

The polarization detection is significant ($\approx 17\sigma$) both integrating over energy and rotational phase, with a measured polarization degree (PD) $13.5 \pm 0.8\%$ and polarization angle (PA) $48.5° \pm 1.6°$ measured East of the celestial North. More in detail, we found a low polarization degree at low energies ($\approx 15\%$ between 2 and 4 keV), where the polarization orientation is $\approx 50°$; then the polarization fraction drops to 0 at around 5 keV, raising again at high energies (6–8 keV) up to $\approx 35°$, with a polarization angle $\approx -40°$ (see Fig. 3). Hence, a net 90° swing of the polarization angle is detected going from lower to higher energies. This is compatible with the presence of photons polarized in two normal modes, that we have interpreted as the ordinary and the extraordinary ones, as expected in the presence of strong magnetic fields.

Interpreting this result within the RCS scenario, the value of polarization degree we obtained at high energies is compatible with the limit (33%) we expect in case RCS is effective in the magnetosphere (see [18]). In this case, a PL tail should dominate the spectrum at those energies (as discussed above for the spectral analysis) and photons should be polarized in the extraordinary mode. According to the observed polarization direction swing, low-energy photons should be, instead, polarized in the ordinary mode; this, together with the low polarization degree detected between 2 and 4 keV, points towards the condensed surface model. Indeed, comparing the data with a Monte Carlo simulation obtained with the code described in [15], assuming that the emitting region is limited to a (magnetic) equatorial belt (where the surface temperature is expected to be low enough to allow for magnetic condensation), the value of polarization degree

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and angle obtained are in good agreement (within the 1σ confidence contours) with the IXPE data (stars in Fig. 3).

We also explored possible different interpretations. Still within the RCS model, one can assume that low-energy, thermal photons are reprocessed in an atmospheric layer above the surface, instead of being emitted directly from the stellar solid surface. Given the low polarization degree observed at different energies, this atmosphere should not be a standard, cooling atmosphere. However, in the case of magnetars, the atmosphere can be bombarded by the returning currents streaming along the closed field lines (see e.g. [20]). Under this assumption, top atmospheric layers may be hotter than the lower ones, contrary of what happens for standard atmospheres. In this way, the photosphere of ordinary photons may lie at a higher temperature than that of extraordinary ones, easily explaining the excess of ordinary photons at low energies. The excess of extraordinary photons at high energies may still be justified by the occurrence of RCS in the magnetosphere.

One can also consider that low-energy photons are polarized in the X-mode and high-energy ones in the O-mode, contrary to what was assumed before; this leads outside the RCS scenario. In order to have an excess of extraordinary photons at low energies at the observed polarization degree, one can think that surface-emitted photons are reprocessed in a corona around the magnetar, where they undergo unsaturated comptonization. In this case, however, it is difficult to reproduce the polarization angle swing at the right energy, as well as to re-obtain the observed polarization degree at higher energies[1]. Recently, Lai [21] suggested that partial mode conversion at the vacuum resonance in a standard, magnetized cooling atmosphere may be responsible for the polarization angle swing at the observed energy (≈ 5 keV). However, the model is still preliminary, and it cannot reproduce the polarization degree IXPE observed at low and high energies.

A phase-dependent polarization analysis in the 2–8 keV band resulted in a double-peak profile of PD, resembling that of the observed flux; on the other hand, PA turned out to be single peaked and well fitted by a rotating vector model (RVM, [22], see Fig. 4). This suggests that the polarization fraction is likely determined close to the star surface, while the polarization direction properties are defined far from the surface. Although the detected polarization degree ($\lesssim 35\%$) does not allow us any conclusive statement in favor of an indirect probe of vacuum birefringence, we remark that the observed phase-dependent behavior of PD and PA are exactly those we expect if vacuum birefringence is effective. In fact, photon polarization vectors are expected to change continuously close to the surface (within the so-called "adiabatic region", see [6,9]) following the magnetic field direction; in this way, the polarization angle trend should reflect the magnetic field topology at $r_{\rm pl}$, while the polarization fraction at the surface is preserved up to large distances from the neutron star.

[1] A possible scenario to produce an excess of O-mode photons at high energies is considering another coronal region, where photons can experience saturated comptonization, but a detailed model in this sense is still lacking.

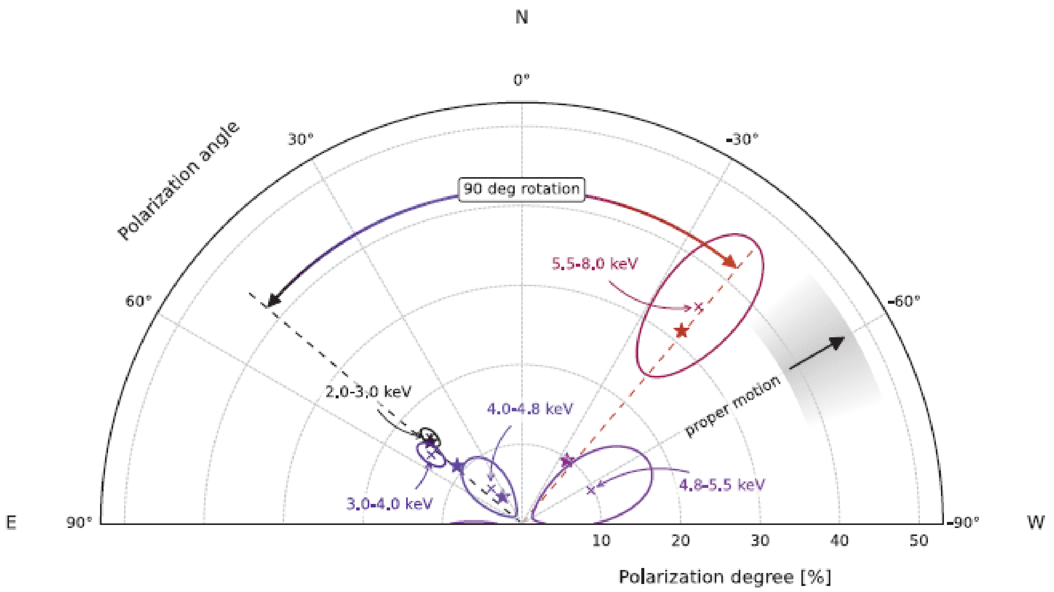

Figure 3: Energy dependent polarization degree (radial coordinate) and polarization angle (azimuthal coordinate) measured for 4U 0142+61 by IXPE (crosses with 1σ confidence contours) and simulated assuming condensed surface emission from an equatorial belt and reprocessed by RCS in the magnetosphere (stars). The proper motion measured for the star by [23] with its uncertainty is also reported (black arrow with gray shaded region). Image taken from [18].

3.2 1RXS J170849.0–4009100

The second magnetar source, the AXP 1RXS J170849.0–4009100 (hereafter 1RXS J1708 for short), has been observed by IXPE between September 19th and October 8th, 2022, for a total exposure time of 837 ks [24]. It is the second brightest among the magnetar candidates (with an observed unabsorbed flux $\sim 3 \times 10^{-11}$ erg cm^{-2} s^{-1} in the 2–10 keV energy band, [25]). In this case, a single peak profile (pulsed fraction $\approx 30\%$) has been detected in the IXPE energy band, with $P \approx 11$ s and $\dot{P} \approx 2.27 \times 10^{-11}$ s s^{-1}, for a spin-down magnetic field intensity $B_{\rm sd} \approx 5 \times 10^{14}$ G.

For this source we exploited a quasi-contemporary observation by NICER and another observation (not much far in time) by Swift-XRT. Putting together the data collected by these instruments and the IXPE observation, we could perform a proper spectral analysis in the 1–8 keV band, helping in constraining also the column density for interstellar absorption. As in the case of 4U 0142+61, both the BB+PL and the BB+BB spectral decompositions provide good fits to the data ($\chi^2 = 406$ and 410, respectively, for 408 dof).

The phase-averaged polarization measurements performed integrating over the IXPE band are highly significant (23σ), with a polarization degree $\approx 35\%$ and polarization direction $\approx -60°$ (East of North). As in the previous source, low-energy radiation (2–3 keV) turned out to be weakly polarized ($\approx 20\%$); however, at variance with 4U 0142+61, the polarization degree increases monotonically with energy, reaching up to a value larger than 80% at high energies (6–8 keV), the highest value detected by IXPE as yet. The polarization direction is, instead, constant at 60° West of the celestial North (see Fig. 5).

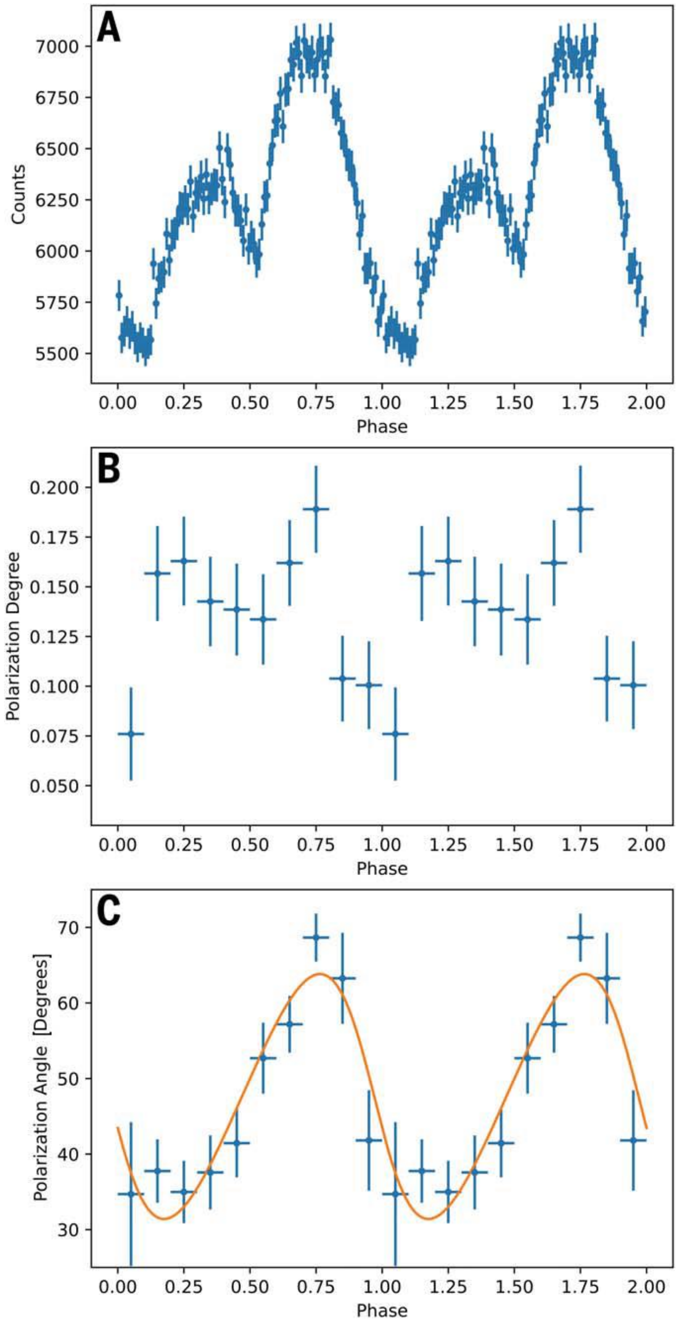

Figure 4: Flux (A), polarization degree (B) and polarization angle (C) as functions of the rotational phase as measured by IXPE for 4U 0142+61 (cyan points with 1σ error bars). The orange solid line in the bottom panel represents the best fit of the PA data with a RVM. Image taken from [18].

In the case of this source, the high polarization observed at high energies, compared with the 33%-limit we expect at high energies within the twisted-magnetosphere scenario, suggest that RCS is not effective in the magnetosphere of this source. On the other hand, the spectral analysis demonstrates that a purely thermal (BB+BB) decomposition provides as well a good fit of data. Hence, we could ascribe high-energy radiation to photons coming from a hotter region of the surface. Under this assumption, the high polarization degree ($\gtrsim 80\%$) is compatible with the presence of a standard, magnetized atmosphere above the star surface. However, this interpretation conflicts with the low polarization degree ($\lesssim 40\%$) observed between 2 and 4 keV, suggesting that the emission geometry is more complex.

Since low polarization is expected if radiation comes directly on the solid, condensed surface of the neutron star, we considered two different scenarios, characterized by the coexistence of atmospheric and solid surface regions on the surface. In the first one we assume that high-energy photons are emitted from a hot polar cap, covered by a cooling NS atmosphere; then, as the temperature decreases (towards the magnetic equatorial region), magnetic condensation may allow the condensed surface to remain exposed, implying a phase transition across the surface of the same neutron star. In the second scenario the two contributions (atmospheric and solid surface ones) come from two spots placed in different regions of the surface (not necessarily polar/equatorial). We checked that both these scenarios can well reproduce the spectral shape, as well as the phase- and energy-dependent polarization properties observed by IXPE.

In addition, we checked that also for this source the phase-dependent polarization degree and angle behave as expected if vacuum birefringence effects are correctly considered in the simulation (see [24] for more details). A quick comparison between the expectations of our two models and the observed data revealed a qualitative agreement if the line-of-sight and magnetic dipole axis inclinations with respect to the rotation axis are $\chi \approx 30°$ and $\xi \approx 10°$, respectively, and the hottest spot on the surface covers $\approx 3-6\%$ of the entire surface. This turns out to be in agreement with the analysis of the hard X-ray emission preformed by [26] for several observations of the same source. In fact, fitting the data with the coronal outflow model developed by [27] (according to which magnetar hard X-ray emission arises from decelerating electron-positron particles in the star magnetosphere), they found that the emission from 1RXS J1708 above 10 keV is compatible with values of $\chi \approx 25°$ and $\xi \lesssim 9°$, and a spot dimension $\approx 5\%$ of the NS surface. Hence, the result obtained in [24] seems to independently recover, at least qualitatively, these previous results.

3.3 SGR 1806–20

The Soft-gamma repeater (SGR) 1806–20 is a famous isolated neutron star source, which has been observed to emit the most powerful giant flare among magnetar candidates in December 2004 [28]. It was in a moderate burst-emitting phase just before the IXPE observation, performed between March 22nd and April 13th, 2023, for a total exposure time of 947 ks [29]. The observed flux ($\approx 4 \times 10^{-12}$ erg cm^{-2} s^{-1}) was unexpectedly lower than what reported in the last observations [30–31] and, in addition, the IXPE observation was affected by a large number of solar flares, that needed to be removed, dramatically reducing the statistics in the IXPE measurement. Nevertheless, a contemporary observation by XMM-Newton (with exposure time 45 ks) allowed us to perform proper timing and spectral analyses in the 1–12 keV band. A double-peaked profile (pulsed fraction $\approx 5\%$) was observed, with spin period $P = 7.77$ s, while, given the lack of a clear detection of pulsations in the IXPE light curve and the short exposure time of the XMM-Newton observation, no constraint on the spin-down rate has been possible. However, assuming a linear increase of the spin period with time (as suggested by previous observations, see [31]), a spin-down rate $\dot{P} \approx 8 \times 10^{-11}$ s s^{-1} (compatible with the values found in the litera-

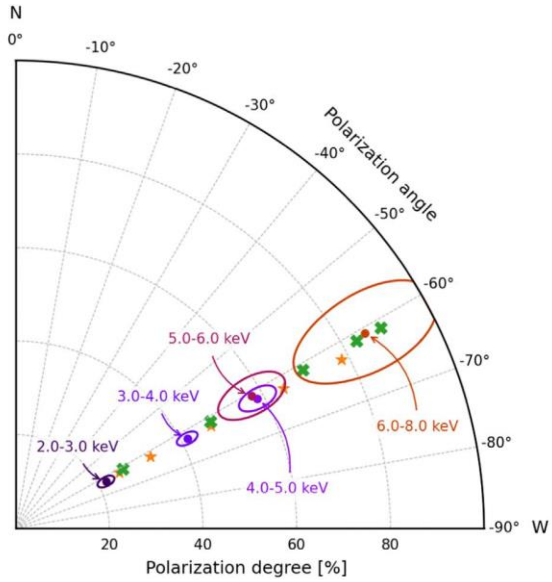

Figure 5: Energy dependent polarization degree (radial coordinate) and polarization angle (azimuthal coordinate) measured for J1708 by IXPE (filled circles with 1σ confidence contours) and simulated assuming a) a hot polar cap covered by a magnetized NS atmosphere plus condensed surface emission from an equatorial (orange stars) and b) emission from an atmospheric and a condensed surface hot spots (green crosses). Image taken from [18].

ture) can be derived. This allows one to estimate a magnetic field strength for spin-down $B_{\rm sd} \approx 8 \times 10^{14}$ G, the strongest one among magnetar candidates.

The XMM spectrum is well fitted by either a BB+BB or a BB+PL decomposition (considering interstellar absorption), returning both a $\chi^2 = 351$ for 298 dof. However, there are elements to prefer the latter spectral model; in fact, the BB+PL decomposition is commonly accepted to explain the spectral shape of persistent magnetars (in particular SGR 1806–20) and a PL tail was detected even in previous NuSTAR observations of the source (see e.g. [30–31]). Moreover, fitting the IXPE spectrum for the 3 DUs using the same decomposition and freezing the fit parameters to those obtained for XMM data gives a statistically acceptable fit ($\chi^2 = 129$ for 162 degrees of freedom).

Owing to the low statistics, the polarimetric analysis was not very significant. The phase- and energy-integrated polarization degree turns out to be 6%, below the minimum detectable polarization at 99% confidence level ($\rm MDP_{99}$, [32]); consequently, the polarization direction is unconstrained. A probable detection (significant at 99% confidence level) has been possible only in a restricted energy band (4–5 keV), with PD $= 31.6 \pm 15.9$ % and PA $= -17.6^{+15.5}_{-15.0}$ degrees (East of North, see Fig. 6). In the rest of the IXPE band, only upper limits were possible, with PD $< 24\%$ between 2 and 4 keV and PD $< 55\%$ between 5 and 8 keV, at 3σ level. This marginal detection indicates that the X-rays from SGR 1806–20 are likely polarized, although the observed flux was too low for a significant measurement in a 1 Ms observation.

Nevertheless, a qualitative comparison with the results of the first two magnetar sources observed allows us to exclude (at 3σ level) a high degree of polarization at high energies (as measured in 1RXS J1708). On the other hand, the possible detection of PD $\sim 30\%$ at 4–5 keV does not exclude a scenario compatible with the presence of a condensed surface emitting region, with photons reprocessed by RCS in the magnetosphere (as observed in 4U 0142+61). In this respect, we checked that a condensed surface+RCS model is indeed able to reproduce the XMM light curve, and the same best fitting model is compatible with the energy-dependent behavior of the polarization degree obtained from IXPE.

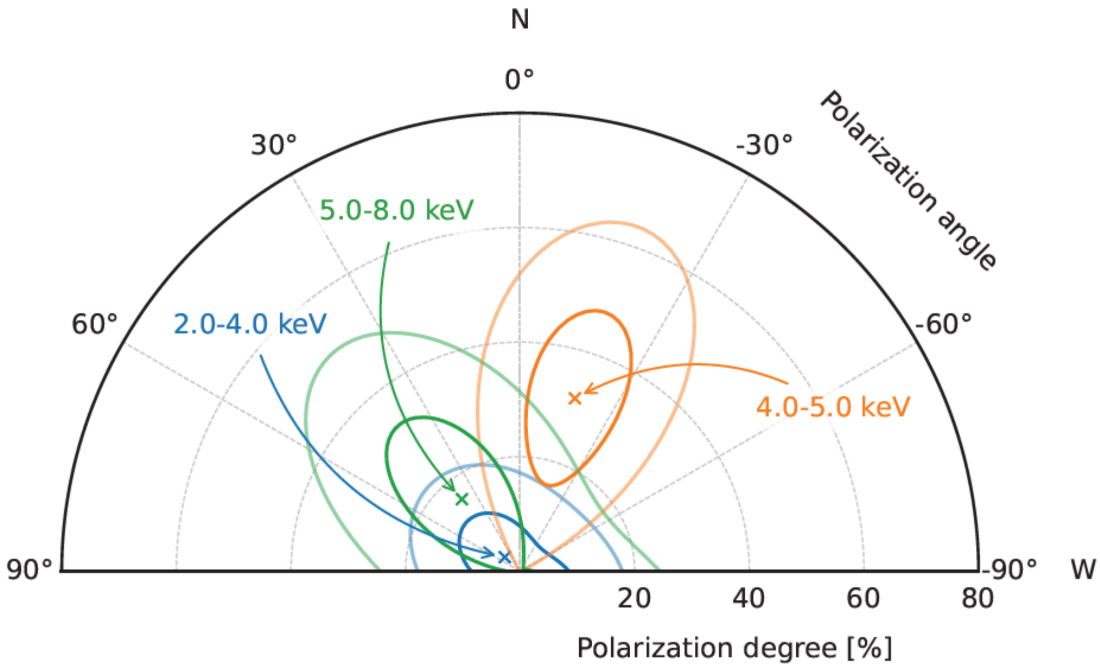

Figure 6: Energy dependent polarization degree (radial coordinate) and polarization angle (azimuthal coordinate) measured for SGR 1806–20 by IXPE (crosses with 68% and 99% confidence contours). Image taken from [29].

4. Conclusions

In this work we summarized the results of the IXPE observations of the persistent X-ray emission from 3 bright magnetar sources. In the case of the two brightest targets, the measurements have been significant enough to provide a physical interpretation. In particular, the detection of two orthogonal polarization directions across the IXPE band for the AXP 4U 0142+61 argues if favor of the hypothesis that magnetars are indeed associated with strongly magnetized environments, where photons are expected to be linearly polarized in two normal modes (O and X). The level of polarization observed at higher energies ($\sim 30\%$), together with the low polarization degree detected at lower ones, suggests the possibility that radiation comes from the solid, condensed surface of the neutron star, reprocessed by charged particles streaming along the closed field lines via RCS.

The very high polarization degree IXPE observed at high energies in the case of the AXP 1RXS J1708, instead, is compatible with emission from a magnetized atmospheric layer covering the neutron star surface. However, the lower PD detected at low energies cannot be easily reconciled with the presence of such an atmosphere, suggesting that probably another, distinct emitting region is present on the surface, in which the solid surface of the star is left bare.

Comparing the phase-dependent data with theoretical model expectations, we obtained results in qualitative agreement with those presented in previous works (see [26, 27]) relative to the hard X-ray emission of 1 RXS J1708.

The third magnetar target, SGR 1806–20, turned out to be too faint for a significant polarimetric analysis with IXPE in the 1 Ms dedicated observation. Still, the derived upper limits, as well as the marginal detection obtained at around 4–5 keV, may indicate that the source is indeed polarized, and further observing time can help in improving the statistical significance of the present measurement.

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DISCUSSION

DANIELE FARGION's comment: 1999–2000s → GRB model = fireball = spherical explosion → Ruled. Last decade probed GRB = jets: very possibly precessing one.

DANIELE FARGION: Early SGR = GRB, signature still similar → SGR = magnetar ←→ explosion? However, jets are more fit to explain the rapid (thin angles) repeating nature, see e.g. [33,34].

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ROBERTO TAVERNA: The first two magnetar sources observed by IXPE, with a positive X-ray polarization detection, are AXPs. The only SGR observed up to now by IXPE is SGR 1806–20, for which, however, no significant detection of X-ray polarization has been possible. Nevertheless, SGR 1806–20 has been observed in its quiescent state, with a low flux level in the soft X-ray band and a quite small pulsed fraction. This persistent emission exhibits the same spectral and timing features before and after the source entered in an active phase (see e.g. [28, 35]), including the giant flare emitted on December 27, 2004, and it is compatible with emission of several other (not anomalous) X-ray pulsars (see e.g. [36–38]). This makes it reasonable to interpret the persistent emission from SGR 1806–20 within the commonly-accepted magnetar model, assuming that pulsating radiation originates from one or more hotter regions on the surface of the star which come into view at different times during the star rotation.

ŞŌLEN BALMAN: The magnetar 4U 0142+61 has a circumstellar fossil disk around. Does that have effect on the observed X-ray polarization? You mentioned mostly reprocessing (atmospheric effects) on the X-rays → polarization. Why not reprocessing in the fossil disk? Could that help to explain the differences of detected polarization on your set of magnetars.

ROBERTO TAVERNA: As mentioned in [39], where the discovery of the debris disk around the AXP 4U 0142+61 is discussed, radiation reprocessed by the fossil debris disk has been identified in the IR counterpart of the source, between 4.5 μm and 8.0 μm. Indeed, as stated in [39], the fossil disk is believed not to power the X-ray emission from the source, being the detected mid-infrared component the result of the passive illumination of the disk by the persistent X-ray coming from the source. This is furtherly confirmed by IXPE which, despite the imaging capability for resolving extended sources [3], detected 4U 0142+61 as a point-like source. The optical and IR counterparts of the source were also investigated in polarized light by [40], showing essentially no polarization. This argues in favor of a different origin of the X-ray and optical/IR radiation from this neutron star.