Polarized x-rays from a magnetar

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Magnetars are neutron stars with ultra-strong magnetic fields, shining in the x-rays. Polarization measurements can probe their magnetic fields and the physics of their surface. We report on the detection of polarized x-rays from the magnetar 4U 0142+61. Observations with the Imaging X-ray Polarimetry Explorer show a linear polarization degree of $13.5 \pm 0.8\%$ averaged over the 2–8 keV band. The polarization changes with energy: the degree is $15 \pm 1\%$ at 2–4 keV, drops below the instrumental sensitivity around 4–5 keV, and rises to $35.2 \pm 7.1\%$ at 5.5–8 keV. The polarization angle also changes by 90° around 4–5 keV. These results are consistent with a model in which thermal radiation from the magnetar surface is reprocessed by scattering from charged particles in the magnetosphere.

Isolated neutron stars (NSs) with extremely strong magnetic fields are referred to as magnetars (*1*). The magnetar population is growing and there are about 30 confirmed sources (*2*), many of which detectable only during periods of enhanced activity. Magnetar emission is powered by the magnetic field, producing bursts of hard ($\approx 10-100$ keV) x-rays, with luminosity $L \approx 10^{38}$–10^{47} erg s^{-1} and duration ≈ 0.1–100 s. Magnetars also exhibit steady x-ray pulsed emission at $L \approx 10^{33}$–10^{35} erg s^{-1}, spin frequencies $f \approx 0.1$–10 Hz and spin-down rates, $\dot{f} \approx -(10^{-16}$–$10^{-8})$ Hz s^{-1}. This indicates magnetic fields $B \lesssim 10^{15}$ G, assuming a standard spin-down model (*3*). The $0.5-10$ keV spectrum of magnetars consists of a blackbody (BB) component (with temperature ~ 0.1–1 keV) and a power-law (PL; photon index $\Gamma \sim 2$–4) dominating above ~ 4–5 keV (*2, 3*). Some sources exhibit a second BB component instead of the PL. Many magnetars are detected in x-rays up to ≈ 200 keV, where the spectrum is dominated by a PL.

The magnetic field surrounding magnetars is expected to differ from a pure dipole, with a non-negligible toroidal component which twists the field lines. Because charged particles flow along closed magnetic field lines, as required to sustain the field, the region threaded by the magnetic field (the magnetosphere) becomes optically thick to Compton scattering at the cyclotron resonance [resonant Compton scattering, RCS, (*4*)]. The BB spectral component is expected to be emitted by (multiple regions on) the cooling surface of the neutron star, while the PL originates from the reprocessing of thermal photons via resonant up-scattering in the magnetosphere (*3*).

Magnetar x-ray persistent emission is expected to be linearly polarized in two orthogonal modes, referred to as ordinary (O) and extraordinary (X), with the polarization vector either parallel or perpendicular to the plane of the photon propagation direction and the (local) magnetic field (*5*). The expected polarization degree of the emitted radiation strongly depends on the physical state of neutron star external layers. If radiation comes from the bare, condensed surface, the polarization is expected to be $\lesssim 10\%$, but a magnetized atmosphere can produce polarization $\lesssim 80\%$ (*6–8*). The polarization of outgoing photons is then modified by RCS, leading to a polarization degree $\lesssim 30\%$ in the X-mode for the PL component, independent of the initial polarization state of the thermal photons (*7–9)*.

Because NSs cannot be spatially resolved by observations, contributions from regions with different magnetic field orientations (therefore with different emitted polarization orientations) are blended together, which reduces the observed polarization (*10, 11*). However, if the magnetic field is strong enough (*5*), it forces the photon polarization vectors to follow the magnetic field direction, resulting in an observed polarization almost unchanged from that at the emission (*10, 11*).

The magnetar 4U 0142+61 (right ascension 01h 46m 22.41s, declination 61° 45’ 03.2”) has a persistent (lightly variable) x-ray flux of $\sim 6 \times 10^{-11}$ erg s^{-1} cm^{-2} in the 2–10 keV range, spin frequency $f = 0.12$ Hz and frequency derivative $\dot{f} = -2.6 \times 10^{-14}$ Hz s^{-1}; implying spin-down (equatorial) magnetic field $B \sim 1.3 \times 10^{14}$ G (*2, 12*). It is visible at infrared and optical wavelengths (*13*), but no (pulsed) radio emission has been detected.

We observed 4U 0142+61 with the Imaging X-ray Polarimetry Explorer [IXPE, (*14*)] between 2022 January 31 and 2022 February 27 for a total on-source time of 840 ks. IXPE provides imaging polarimetry over a nominal energy band of 2–8 keV. The data were extracted and processed according to standard procedures (*15*). Pulsations were detected at $f = 0.115079336 \pm 6 \times 10^{-9}$ Hz with $\dot{f} = -(2.1 \pm 0.7) \times 10^{-14}$ Hz s^{-1} [Modified Julian Date (MJD) 59624.050547; uncertainties are 68.3% confidence, see Figure S3 in (*15*)], consistent with previous measurements within the uncertainties (*12*). We performed a spectral analysis using the software package XSPEC (*16*), version 12.12.1. The data are not consistent with a single-component model, so we considered several two-component models *(15)*. In all models we fixed the value of the interstellar column density to 0.57×10^{22} cm^{-2} (*17*) which cannot be constrained by the IXPE data because of the insufficient sensitivity below 2 keV. The parameters we found for a BB+PL model (Table S2) are consistent with previous measurements (*17, 18*).

Polarization was measured by extracting the (calibrated) Stokes parameters I, Q and U from each photon collected by the three independent IXPE detector units (DUs). After subtracting the sky background, the contributions of each DU were combined, accounting for the 120° offset between the DUs. Figure 1 shows the phase-averaged, normalized Stokes parameters (Q/I and U/I) in the 2–8 keV energy range, for the individual DUs and the combined value. The phase-averaged, energy-integrated values are $Q/I = 0.013 \pm 0.008$ and $U/I = 0.120 \pm 0.008$, implying a polarization degree, PD $\equiv \sqrt{Q^2 + U^2}/I$, of $13.5 \pm 0.8\%$ and a polarization angle, $PA \equiv \arctan(U/Q)/2$, of $+48.5^\circ \pm 1.6^\circ$, with positive values being East of (local celestial) North; uncertainties are 1σ. These values were derived using two different methods, with consistent results (*15*). We determined that the minimum detectable polarization at 99% confidence level (MDP_{99}) for our observation is $\sim 2\%$ over the 2–8 keV range, so the significance of the non-zero polarization degree is $\sim 18\sigma$.

To investigate whether the PD and PA depend on the photon energy, the data were grouped into 5 energy bins selected to contain similar numbers of counts in each bin. Figure 2 shows a polar plot of the results. We find the PD is $15.0 \pm 1.0\%$ at low energies ($\sim$ 2–4 keV), $\sim 10\sigma$ above the MDP_{99}, which is $\sim 4\%$. At 4–5 keV the PD is consistent with zero. In the highest energy bin (5.5–8 keV), the PD is $35.2 \pm 7.1\%$, above the MDP_{99} which is $\sim 21\%$. The PA is about 50° at energies below 4 keV and -40° above 5 keV, a swing of 90°.

We also performed a spectro-polarimetric analysis, by separately convolving the low- and high-energy spectral components with a constant polarization model (POLCONST in XSPEC). This confirms the 90° swing in polarization angle for all the two-component spectral models: BB+BB, BB+PL and BB+Truncated PL *(15)*. For the latter model, the derived PD for the two components is within $\sim 1\sigma$ from the observed values, with the low energy BB component being less polarized than the high-energy PL (*15*).

To perform a phase-dependent analysis, we divided the flux into 100 phase bins and used an unbinned maximum likelihood technique (*19*) to determine the PD and PA. Figure 3A shows the resulting pulse profile, which is double-peaked as in previous observations (*18*). Phase variations are evident in both PD and in PA (Fig. 3B–3C), with amplitudes of $\sim 10\%$ and $\sim 30^\circ$, respectively. At low energies (2–4 keV), we find the main and secondary peaks have higher polarization fraction ($\sim 15\%$) than the phase valley between them ($\sim 9\%$). In contrast, the phase-resolved PA is single peaked. This is as predicted by pulsar models discussed in the literature [i.e. the rotating-vector model (*20*)], although the strong degeneracy prevents to recover the NS spin and magnetic axes orientations from fitting the PA data [see (*15*)].

A phase-resolved spectral analysis of 4U 0142+61 shows no statistically significant dependence of the spectrum on rotational phase. The blackbody component is compatible with being constant in phase (Fig. S5). The same result was obtained in (*21*) and is consistent with the low pulsed fraction ($\sim 5\%$) below 3–4 keV detected in a previous observation more sensitive at low energies (*18*).

We considered the IXPE results within the twisted-magnetosphere model (*4*), accounting for the quantum electrodynamical effect of vacuum birefringence (*7–9*). The observed polarization pattern as function of energy, with a minimum PD and a 90° swing of PA at 4–5 keV, indicates that the 2–8 keV x-ray emission from 4U 0142+61 has two distinct components, polarized in two different normal modes, corresponding to the two components identified in the spectral analysis. In this framework, the low-energy component is produced by thermal emission from the surface of the neutron star, while the high-energy component is produced by photons scattered to higher energies in the magnetosphere (Figure 4A). The measured polarization fraction at high energies ($\sim 35\%$ at 5.5–8 keV) is compatible with the theoretical prediction of the RCS model (*7*) and indicates that X-mode photons dominate at high energies; conversely, O-mode photons dominate at low energies.

Theoretical models for magnetar surface emission of soft x-rays predict either i) a large ($\gtrsim$ 50%) polarization degree in the X-mode if there is a gaseous atmosphere heated from below (*22*), or ii) a small $\lesssim 10\%$ polarization degree in the O-mode, if there is a condensed (solid/liquid) surface (*6–8, 23*). The IXPE measurement below 4 keV is not compatible with the presence of an atmosphere and are only marginally compatible with a condensed surface. The latter would be more consistent with the data if the PD could be raised in the model, perhaps by thermal radiation being emitted by only a limited region, not the entire surface (as was assumed in previous calculations). The low pulsed fraction at low energies *(18)* indicates an extended emitting area. Using the numerical code discussed in (*7*), we found that radiation from an iron condensed surface emitted from an equatorial belt produces O-mode photons at low energies (2–4 keV) with PD $\sim$ 15%. Reprocessing by RCS then produces an excess of X-mode photons at higher energies (5.5–8 keV) with PD $\sim$ 35%, while PA changes by 90°. We remark that our calculation does not assume that the reference direction in the plane of the sky (from which PA is computed) coincides with the projection of the NS spin axis. To match the measured and predicted (absolute) values, an offset is added to the simulated PA [see (*15*)]. Figure 2 shows the results of the numerical simulation for a magnetic field strength $\sim 10^{14}$ G, as derived for 4U 0142+61 (*18*), and using the emissivities of a magnetized iron condensate discussed in (*23*), in the “fixed-ion” approximation. A hotter belt close to the magnetic equator appears in NS magneto-thermal evolution calculations, both in 2D and 3D (*24*, *25*).

We also consider alternative models to explain the IXPE data. Within the RCS paradigm, low-energy O-mode photons could be produced by a gaseous layer with an inverted temperature profile, with a downward flow of energy as might be produced by external particle bombardment (*26*). In this case, O-mode photons would escape from a deeper (and so hotter) region with respect to a passively cooling atmosphere, and dominate the outgoing flux.

In an alternative scenario, the low-energy emission could be interpreted as polarized in the X-mode and the high energy emission, above 4–5 keV, in the O-mode. Low-energy, X-mode dominated emission with a low polarization degree ($\sim$ 15%) could originate from an extended region of a condensed iron surface seen few degrees away from the magnetic axis. Radiation from a thin atmosphere or corona, in the presence of thermal photons undergoing Compton scattering (*8*) could produce the observed polarization at low energies. However, this scenario does not explain how O-mode photons would dominate the emission in the 5–8 keV band. Saturated Compton scattering in a thin atmosphere or corona (*8*) or emission from an electron-positron plasma (*27*) could potentially produce O-mode dominated radiation (Figure 4B), but these models predict a much higher PD than is observed. Emission from a small region of the surface that is covered by an externally illuminated gaseous layer but hot enough to dominate the high-energy band, would also produce substantial polarization in the O-mode. No detailed modeling of these scenarios is available.

Identifying the mode in which the observed x-ray photons are predominantly polarized would determine the orientation of the magnetar spin axis projected onto the plane of the sky. The phase-averaged PA is 0° (or 90°) for radiation mostly polarized in the O-mode (or X-mode), taking the reference direction in the plane of the sky to be along the spin axis projection (*10*). If O-mode photons dominate at low energies where PA$\sim 50°$, as in the RCS model, the projection of the spin axis would be $\sim 50°$ East of North. Conversely, if low-energy photons are polarized in the X-mode the spin axis projection would be $\sim 40°$ West of North. In the latter case, the spin projection would be consistent with the direction of the magnetar proper motion, $60° \pm 12°$ West of North (*28*) [Figure 2], while in the former case the two would be almost orthogonal. It is unclear which is more appropriate for magnetars. Observations of pulsars (including the Crab Pulsar and Vela Pulsar), a different type of neutron star, show alignment of the spin axis with the proper motion (*29*). On the other hand, binary star evolution theory predicts that neutron stars should be accelerated perpendicular to the spin axis during their formation process (*30*). We are unable to distinguish between these possibilities.

We have detected (linearly) polarized x-ray emission from the magnetar 4U 0142+61. The polarization properties vary with x-ray energy, including a 90° swing of the polarization angle. These observations can be explained by a model of emission from the bare condensed surface of the NS, reprocessed by RCS in a twisted magnetosphere. Alternative explanations are also possible.

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Acknowledgments: We thank three anonymous referees for helpful and constructive comments that improved the paper.

This paper is based on observations made by the IXPE, a joint US and Italian mission. The US contribution to the IXPE mission is supported by NASA, led and managed by the MSFC, with industry partner Ball Aerospace (contract NNM15AA18C). The Italian contribution is supported by ASI through contract ASI-OHBI-2017-12-I.0, agreements ASI-INAF-2017-12-H0 and ASI-INFN-2017.13-H0 and the SSDC with agreements ASI-INAF-2022-14-HH.0 and ASI-INFN 2021-43-HH.0, and by INAF and INFN. Data products were provided by the IXPE Team (MSFC, SSDC, INAF and INFN) and distributed with additional software tools by the High-Energy Astrophysics Science Archive Research Center (HEASARC) at NASA GSFC.

Funding: R. Ta. and R. Tu. acknowledge financial support from the Italian MUR through grant PRIN 2017LJ39LM. JH acknowledges the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), funding reference number 5007110, and the Canadian Space Agency. DGC is a Canadian Institute for Theoretical Astrophysical (CITA) National Fellow and thanks the support of NSERC (grant #CITA 490888-16). EG and HK acknowledge NASA support under grants 80NSSC18K0264, 80NSSC22K1291, 80NSSC21K1817 and NNX16AC24G. M. Ne. acknowledges support from NASA under award 80GSFC21M0002. TT was supported by Grant JSPS KAKENHI JP19H05609. SB, RF, GM, Ma. Pe. and P. So. were supported by ASI and INAF under grants ASI-INAF-2017-12-H0 and ASI-INAF-2022-14-HH.0. LB was supported by ASI and INFN under grants ASI-INFN-2017.13-H0 and ASI-INFN-2021-43-HH.0.

Author contributions: R. Ta., R. Tu., FM, JH, SZ, LB, JR and MCW planned the observing campaign. R. Ta., R. Tu., FM, JH, SZ, LB, JR, DGC, MB, IC, NDL, EG, DK, HK, M. Ne., M. Ng, NO, AP, TT, KU analyzed the data. R. Ta., R. Tu., FM, JH, SZ, LB, JR, DGC, MB, IC, AP, TT, KU modeled the data. R. Ta., R. Tu., FM, JH, SZ, LB, JR, DGC, MB, AP wrote the manuscript. VD and ME served as internal reviewers. All the other authors contributed to the design, science case of the IXPE mission and in the planning of observations relevant to the present paper. All the authors provided input and comments on the manuscript.

Competing interests: The authors declare that they have no competing interests.

Data and materials availability: The IXPE observation of 4U 0142+61 is available in the High Energy Astrophysics Science Archive Research Center (HEASARC) IXPE Data Archive https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/ under ObsID 01003299. The IXPE software is publicly available at https://github.com/lucabaldini/ixpeobssim and https://ixpeobssim.readthedocs.io/en/latest/?badge=latest. The HEASARC developed the HEASOFT (HEASARC Software). The measured polarizations are listed in Table S2 and the results of our model fitting are listed in Tables S1 and S3.

Supplementary Materials

Materials and Methods

Figs. S1 to S10

Tables S1 to S3

References (*31*–*56*)

Fig. 1. Normalized, background-subtracted Stokes parameters Q/I and U/I for x-ray emission from 4U 0142+61.
The values measured from each of the three IXPE DUs (in the 2–8 keV range) are marked by green, orange and blue dots with 1σ error bars, while their combination obtained using the two approaches discussed in (*15*) are shown in black and gray, respectively. The background circles indicate PD and the radial lines indicate PA, measured East from North. The purple shaded area shows the detection limit (MDP_{99}) for the combined measurement.

Fig. 2. Energy dependence of the measured PD and PA (polar plot).
Crosses indicate the measured values, in labelled energy bins, and contours enclose the 68.3% confidence level regions obtained with XSPEC (*15*). Stars indicate the corresponding PD and PA calculated using the condensed-surface RCS model. The arc bounded by the two dashed lines shows the change in polarization angle from the lowest (2–3 keV, black dashed line) to the highest (5.5–8 keV, red dashed line) energy bins. The black arrow and gray shaded area indicate the proper motion direction of the source and its associated uncertainty (*28*).

Fig 3. Phase-dependent x-ray flux and polarization properties.
(**A**) Energy-integrated (2–8 keV) IXPE counts as a function of spin phase. Error bars are at 1σ confidence level. (**B**) Polarization degree as a function of spin phase. Error bars indicate $\Delta \log L = 1$ of the unbinned likelihood L. (**C**) Same as panel B, but for the polarization angle. The orange curve shows the best-fitting rotating vector model [see (*15*)].

Fig 4. Schematic illustration of the proposed theoretical scenarios.
(**A**) Thermal radiation emitted by an equatorial belt on the condensed surface of the magnetar (or an atmosphere with an inverted temperature gradient), then reprocessed by RCS in the magnetosphere. (**B**) Radiation from the whole surface reprocessed by (unsaturated) thermal Compton scattering in a near-surface atmospheric layer, then additional (saturated) Compton scattering in an extended corona. The darker areas on the NS surface indicate the emitting regions. Black lines with arrows indicate the (dipole) magnetic field lines. The gray boxes along the photon trajectories highlight the polarization plane and the oscillating electric field.