Polarized x-rays from a magnetar

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Magnetars are neutron stars with ultrasmall magnetic fields, which can be observed in x-rays. Polarization measurements could provide information on their magnetic fields and surface properties. We observed polarized x-rays from the magnetar 4U 0142+61 using the Imaging X-ray Polarimeter Explorer and found a linear polarization degree of 13.5 ± 0.8% averaged over the 2 to 8 keV electron-volt band. The polarization changes with energy: The degree is 15.0 ± 1.0% at 2 to 4 kilo-electron volts, drops below the instrumental sensitivity ~4 to 5 kilo-electron volts, and rises to 35.2 ± 7.1% at 5.5 to 8 kilo-electron volts. The polarization angle also changes by 90° at ~4 to 5 kilo-electron volts. These results are consistent with a model in which thermal radiation from the magnetar surface is reprocessed by scattering off charged particles in the magnetosphere.

Isolated neutron stars (NSs) with extremely strong magnetic fields are referred to as magnetars (1). There are ~30 confirmed magnetars known (2), many of which are detectable only during periods of enhanced activity. Magnetar emission is powered by the magnetic field, producing bursts of hard (>10 to 100 keV) x-rays, with luminosity $L \approx 10^{38}$ to $10^{41}$ erg s$^{-1}$ and duration ~0.1 to 100 s. Magnetars also exhibit persistent x-ray emission at $L \approx 10^{33}$ to $10^{35}$ erg s$^{-1}$, which is pulsed at spin frequencies $f \approx 0.1$ to 10 Hz with spin-down rates $f_\nu \approx (10^{-16} \text{to} 10^{-18})$ Hz s$^{-1}$. These properties indicate high magnetic fields $B \approx 10^{12}$ G, assuming a standard spin-down model (3). The 0.5- to 10-keV spectrum of magnetars consists of a blackbody (BB) component (with $kT \approx 0.1$ to 1 keV, where $T$ is the temperature and $k$ is the Boltzmann constant) and a power-law (PL) component with photon index $\Gamma$ ~ 2 to 4; the PL component dominates above ~4 to 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, at which the spectrum is also dominantly by the PL component.

The magnetic field surrounding magnetars is expected to differ from a pure dipole, with a non-negligible toroidal component that 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 frequency [$\text{resonant Compton scattering (RCS)}$ (4)]. The BB spectral component is expected to be emitted by (multiple regions on the) the cooling surface of the NS, whereas the PL originates from the reprocessing of thermal photons through 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 formed by 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 the NS external layers. If radiation comes from the bare, condensed surface, the polarization is expected to be ~100%, but a magnetized atmosphere can produce polarization ~80% (6, 7). The polarization of outgoing photons is then modified by RCS, which leads to a polarization degree ~30% in the X mode for the

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| Deceased |
PL component, independent of the initial polarization state of the thermal photons (7–9).

Because NSs cannot be spatially resolved by observations, the contributions from regions with different magnetic field orientations (and 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, which results in an observed polarization almost unchanged from that at the emission (10, 11).

The magnetar 4U 0142+61 (coordinates right ascension 01h 46m 22s.41, declination 61° 45′ 03″.2, J2000 equinox) has a persistent (lightly variable) x-ray flux of ~6 × 10⁻¹¹ erg s⁻¹ cm⁻² in the 2- to 10-keV range, a spin frequency of \( f = 0.12 \) Hz, and a frequency derivative of \( \dot{f} \equiv 0.115079336 \pm 6 \times 10^{-9} \) Hz s⁻¹. This implies a spin-down (equatorial) magnetic field of \( B \equiv 1.3 \times 10^{14} \) 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 31 January 2022 and 27 February 2022 for a total on-source time of 840 ks. IXPE provides imaging polarimetry over a nominal energy band of 2 to 8 keV. The data were extracted and processed according to standard procedures (15). Pulsations were detected (fig. S3) at \( f = 0.115079336 \pm 6 \times 10^{-9} \) Hz with \( \dot{f} = -(2.1 \pm 0.7) \times 10^{-18} \) Hz s⁻¹ (at MJD 59624.050547, where MJD is the modified Julian date); uncertainties are 68.3% confidence. These values are 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 foreground interstellar column density to \( 0.57 \times 10^{22} \) cm⁻² (17); it cannot be constrained by the IXPE data because of insufficient sensitivity below 2 keV. Our best-fitting parameters 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, which were collected by the three independent IXPE detector units (DUs). After subtracting the sky background, the contributions of each DU were combined to account for the 120° offset between the DUs. Figure 1 shows the phase-averaged, normalized Stokes parameters \( (Q/I) \) and \( (U/I) \) in the 2- to 8-keV energy range for the individual DUs and the combined data. The phase-averaged, energy-integrated values are \( Q/I = 0.013 \pm 0.008 \) \text{ and } \( U/I = 0.120 \pm 0.008 \), which implies a polarization degree \( PD = \sqrt{Q^2 + U^2} / I \) of 13.5 ± 0.8% and a polarization angle \( PA = \arctan(U/Q) / 2 \) of +48.5° ± 1.6°, with positive values being east of (local celestial) north; uncertainties are 1σ. We derived these values using two different methods and found consistent results (15). We determined that the minimum detectable polarization at 99% confidence level (MDP99) for our observation is ~2% over the 2- to 8-keV range, so the significance of the nonzero polarization degree is ~17σ.

To investigate whether the PD and PA depend on the photon energy, the data were grouped into five energy bins, which were selected to contain similar numbers of counts in each bin. Figure 2 shows a polar plot of the results. We find that the PD is 15.0 ± 1.0% at low energies (~2 to 4 keV), ~10σ above the MDP99 of that bin, which is ~4%. At 4 to 5 keV, the PD is consistent with zero. In the highest-energy bin (5.5 to 8 keV), the PD is 35.2 ± 7.1%, where the MDP99 is ~21%. The PA is ~50° at energies below 4 keV and ~40° above 5 keV, a swing of 90°.

We also performed a spectropolarimetric 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 we considered: BB + BB, BB + PL, and BB + truncated PL (15). For the latter model, the derived PD for the two components is within ~1σ of 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 found in previous observations (18). Phase variations are evident in both PD and in PA (Fig. 3, B and C), with
amplitudes of ~10% and ~30°, respectively. At low energies (2 to 4 keV), we find the main and secondary peaks have higher polarization fraction (~15%) than the phase valley between them (~9%). By contrast, the phase-resolved PA is single peaked. This is consistent with the predictions of pulsar (a different type of NS) models [specifically the rotating-vector model (20)], although a strong degeneracy prevents us from determining the NS spin and magnetic axes orientations from the PA data (15).

A phase-resolved spectral analysis of 4U 0142+61 shows no statistically significant dependence of the spectrum on rotational phase (15). The BB component is compatible with being constant in phase (fig. S5), which is consistent with previous results (21) and previous observations of a low pulsed fraction (~5%) below 3 to 4 keV (18).

We considered the IXPE results within a twisted-magnetosphere model (4), accounting for the quantum electrodynamical effect of vacuum birefringence (7–9). The observed polarization behavior as a function of energy—with a minimum PD and a 90° swing of PA at 4 to 5 keV—indicates that the 2- to 8-keV x-ray emission from 4U 0142+61 has two distinct components, polarized in two different normal modes, which correspond 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 NS, whereas the high-energy component is produced by photons scattered to higher energies in the magnetosphere (Fig. 4A). The measured polarization fraction at high energies (~35% at 5.5 to 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 (≥50%) polarization degree in the X mode if there is a gaseous atmosphere heated from below (22) or (ii) a small ≤10% polarization degree in the O mode if there is a condensed (solid or liquid) surface (6–8, 23). The IXPE result below 4 keV is not compatible with the presence of an atmosphere and 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 from 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 a numerical code (7), we calculated that radiation from a condensed iron surface, emitted from an equatorial belt, produces O-mode photons at low energies (2 to 4 keV) with PD ~15%. Reprocessing by RCS then produces an excess of X-mode photons at higher energies (5.5 to 8 keV) with PD ~35%, whereas the PA changes by 90°. Our calculation does not assume that the reference direction in the plane of the sky (from which the 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 (15). Figure 4 shows the results of our numerical simulation for a magnetic field strength ~10¹⁴ G, as measured for 4U 0142+61 (18), assuming the emissivity of an iron condensed surface (23), in the fixed-ion approximation. A hotter belt close to the magnetic equator appears in NS magnetothermal evolution calculations in both two and three dimensions (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 than in a passively cooling atmosphere and would 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 to 5 keV, in the O mode. Low-energy, X mode–dominated emission with a low polarization degree (~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 that are undergoing Compton scattering (27) 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- to 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 (Fig. 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 provide further constraints on the magnetar spin axis. These observations can be explained by a model of emission from the bare condensed surface of the NS that is reproduced by RSC in a twisted magnetosphere. Alternative explanations are also possible.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Tables S1 to S3

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