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Supplementary information

Vacuum birefringence and the polarized X-ray emission from a radio magnetar

In the format provided by the authors and unedited

1 Supplementary Materials

1.1 IXPE data reduction

The Imaging X-ray Polarimetry Explorer (IXPE), launched in December 2021, is the first imaging X-ray polarimetry space observatory. IXPE consists of three identical telescopes sensitive to 2–8 keV with detector units (DU) containing a Gas Pixel Detector (GPD) that images the photoelectron tracks from incoming X-rays [1]. IXPE observed the magnetar 1E 1547.0−5408 between UTC 2025-03-26T03:01:52 (MJD 60760.12629630) and UTC 2025-04-05T00:26:53 (MJD 60770.01866898) for a total livetime duration of 499.5 ks (see Extended Table 2). We applied background rejection via the treatment recommended in [2] using the software *filter_background.py*. No significant solar flaring or bursting activity was detected during this observation. The total number of counts detected in the full IXPE band is 20943. We performed the solar-system barycenter correction of the data using the HEASoft version 6.35 task `barycorr` according to the source J2000 coordinates, R.A = 237.725517°, Dec = -54.306697°[3] with the JPL planetary ephemeris DE405. We subsequently used the pulsar timing package, PINT [4], to assign phases to each photon according to a phase-coherent timing solution that incorporated both radio and X-ray time of arrivals (ToAs) (see Extended Table 1 for details of the full timing solution).

After using DS9 to identify the peak of the centroid of the IXPE observation, we utilized the software `ixpeobssim` version 31.0.1 to perform data cleaning and extract high level data products, including spectra, lightcurves, and binned polarization cubes. The `ixpeobssim` task `xpradialprofiles` allowed us to examine the radial profiles and identify the extraction region size that optimized the data's signal-to-noise ratio. Based on the radial profiles, we selected a circular source region of 0.5' and an annular background with an inner radius of 2.5' and outer radius of 4.5'. For the energy and phase-resolved products, we select the instrument response functions (IRFs) as ixpe:obssim*:v13 from `ixpeobssim`'s pseudo-CALDB which provides the arf, rmf, PSF, vignetting functions, modulation factors, and modulation responses corresponding to the observation date [5]. For the spectral products, we generated the arf and mrf for each detector via the HEASoft tool `ixpecalcarf` and utilized the corresponding responses within Xspec during the spectral fitting. We verified that swapping the ixpeobssim arf and rmf curves with those built with HEASoft, or vice versa, returned consistent results.

The intensity X-ray pulse profiles are binned according to 32 equally spaced bins. The phase-resolved polarization degree and angle, on the other hand, were calculated according to 7 inhomogeneous phase bins to sample the morphology seen in both the radio and the X-ray intensity profiles.

1.2 NICER data reduction

The Neutron star Interior Composition Explorer (NICER) is a non-imaging soft X-ray telescope aboard the International Space Station sensitive between 0.2–12 keV with an effective collecting area of 1900 cm^2 peaking at 1.5 keV. Its superior timing resolution of < 300 nanoseconds makes NICER ideal for tracking magnetar temporal behavior. The data was extracted and cleaned using the HEASoft version 6.35 tool NICERDAS version 13a; the files were calibrated with NICER CALDB version 20240206. We applied standard filtering via the `nicerl2` task. Each photon time of arrival was barycenter corrected to the solar system according to the JPL solar-system ephemeris DE405 using the HEASoft tool `barycorr`. We generated the lightcurves and spectra using the task `nicerl3`, including the NICER spectral background model, SCORPEON which can be simultaneously fit with the source spectra to model sky and non-X-ray background contributions.

1.3 Parkes/*Murriyang* data reduction

We conducted three observations of 1E 1547.0−5408 concurrent to the IXPE campaign using *Murriyang*, the 64 m Parkes radio telescope, with the Ultra-Wideband Low (UWL) receiver system [6]. These observations were collected as part of the long-term Parkes Magnetar Monitoring Programme (project ID: P885). We recorded full Stokes pulsar fold-mode data using the MEDUSA signal processor, where the voltage stream was coherently de-dispersed at $697\,\mathrm{pc\,cm^{-3}}$ to correct for signal dispersion in the interstellar medium and then folded at the rotation period of the magnetar with 1024 phase bins covering each rotation of the magnetar. The data were subsequently averaged in time to form 30 s duration sub-integrations, each containing 3328 frequency channels covering the 704–4032 MHz band of the UWL. The start and end times and duration of each observation are listed in Extended Table 2. We only made use of the data above 2.5 GHz in this work, as multi-path propagation through the interstellar medium induces substantial scatter broadening of the pulse profile below this cutoff frequency, resulting in a smearing of the phase-dependent polarization properties [7]. Radio-frequency interference from artificial sources were excised from the data by flagging and zero-weighting the contaminated frequency channels using the `paz` and `pazi` tools in `psrchive` to first remove known persistently affected channels, and then manually flag any remaining interference [8, 9]. The data were then polarization and flux calibrated following the procedure outlined in Ref. [10] using the full receiver model implemented in the `pac` tool of `psrchive`. Prior to each magnetar observation, we conducted a short, 80 s duration off-source pointing where a linearly polarized switched noise diode of known brightness was injected into the data stream. This was then compared to on/off observations of the calibration source PKS B1934−638 to determine the absolute gain and phase corrections. The polarimetric response of the instrument as a function of parallactic angle was corrected for using a model derived from a rise-to-set track of the bright millisecond pulsar PSR J0437−4725. We then corrected for the effects of Faraday rotation in the Stokes Q and U data due to propagation in the magnetized interstellar medium by applying the known rotation measure of $-1847.6\,\mathrm{rad\,m^{-2}}$ using the `pam` tool with the `--aux_rm` flag to de-rotate the data to infinite frequency.

1.4 Phase-coherent timing analysis

We obtained ToAs from the radio data by cross-correlating the individual frequency-averaged sub-integrations from each observation with a noise-free template via the Fourier-domain Monte Carlo method implemented in the `pac` tool in `psrchive`. The profile template was generated from a set of von Mises functions that were fit to a fully time/frequency averaged copy of the first Murriyang total intensity profile via the `paas` tool. We derived X-ray ToAs from the IXPE and NICER data utilizing the Code for Rotational-analysis of Isolated Magnetars and Pulsars (`CRIMP`). We create an X-ray pulse template from a high S/N NICER profile, which was then fit to a sinusoidal function including only the fundamental harmonic; adding more harmonics did not improve the quality of the fit. We then merge each instrument's event files, and split them into time intervals which incorporate 2000 counts and 4000 counts for NICER and IXPE, respectively, ensuring that each interval is $\lesssim 0.5$ days. Finally, we fit the template to the phase-folded X-ray profiles of each interval, fixing all template parameters except for a phase-shift (i.e., the ToA) and the unpulsed component (which could show mild variability in NICER due to its non-negligible background).

An initial phase-coherent timing solution spanning the IXPE observing campaign was derived from the joint NICER and IXPE X-ray ToAs. We then used the tempo2 pulsar timing package [11, 12] to refine this solution by re-fitting the magnetar spin frequency and spin-down rate while including the radio ToAs, thereby obtaining a locally phase-coherent timing model covering both the radio and X-ray observations. All ToAs were barycentered using the JPL planetary ephemeris DE405. We verified that both epoch-to-epoch and intra-observation variations in the radio pulse profile had a negligible impact on the final timing precision.

To ensure accurate absolute phase alignment between the radio and X-ray data sets, the final timing solution presented in Table 1 was obtained by fitting only the radio ToAs. This ensures that the rotational parameters are properly referenced to TZRMJD, which defines the phase zero-point of the radio profile template used to derive the radio ToAs, along with the associated phase-defining parameters TZRFRQ and TZRSITE. The NICER and IXPE X-ray data were then folded using this final timing solution with PINT [4].

We aligned the three Murriyang observations in phase using the above timing solution, and then averaged all three together in time and frequency to form a single, average polarization profile. The total linear polarization was computed as the quadrature sum of the Stokes Q and U profiles as $L = \sqrt{Q^2 + U^2}$, which was subsequently de-biased using the method outlined in [13].

References

[1] Weisskopf, M. C. *et al.* The Imaging X-Ray Polarimetry Explorer (IXPE): Pre-Launch. *Journal of Astronomical Telescopes, Instruments, and Systems* **8**, 026002 (2022).

[2] Di Marco, A. *et al.* Handling the Background in IXPE Polarimetric Data. *AJ* **165**, 143 (2023).

[3] Deller, A. T., Camilo, F., Reynolds, J. E. & Halpern, J. P. The Proper Motion of PSR J1550-5418 Measured with VLBI: A Second Magnetar Velocity Measurement. *ApJL* **748**, L1 (2012).

[4] Luo, J. *et al.* PINT: High-precision pulsar timing analysis package (2019). ascl:1902.007.

[5] Baldini, L. *et al.* ixpeobssim: A simulation and analysis framework for the imaging X-ray polarimetry explorer. *SoftwareX* **19**, 101194 (2022).

[6] Hobbs, G. *et al.* An ultra-wide bandwidth (704 to 4 032 MHz) receiver for the Parkes radio telescope. *PASA* **37**, e012 (2020).

[7] Camilo, F., Reynolds, J., Johnston, S., Halpern, J. P. & Ransom, S. M. The Magnetar 1E 1547.0-5408: Radio Spectrum, Polarimetry, and Timing. *ApJ* **679**, 681–686 (2008).

[8] Hotan, A. W., van Straten, W. & Manchester, R. N. PSRCHIVE and PSRFITS: An Open Approach to Radio Pulsar Data Storage and Analysis. *PASA* **21**, 302–309 (2004).

[9] van Straten, W., Demorest, P. & Oslowski, S. Pulsar Data Analysis with PSRCHIVE. *Astronomical Research and Technology* **9**, 237–256 (2012).

[10] Lower, M. E., Shannon, R. M., Johnston, S. & Bailes, M. Spectropolarimetric Properties of Swift J1818.0-1607: A 1.4 s Radio Magnetar. *ApJL* **896**, L37 (2020).

[11] Hobbs, G. B., Edwards, R. T. & Manchester, R. N. TEMPO2, a new pulsar-timing package - I. An overview. *MNRAS* **369**, 655–672 (2006).

[12] Edwards, R. T., Hobbs, G. B. & Manchester, R. N. TEMPO2, a new pulsar timing package - II. The timing model and precision estimates. *MNRAS* **372**, 1549–1574 (2006).

[13] Everett, J. E. & Weisberg, J. M. Emission Beam Geometry of Selected Pulsars Derived from Average Pulse Polarization Data. *ApJ* **553**, 341–357 (2001).