The High Energy X-Ray Probe (HEX-P)

Probing Magnetar Physics Through Broadband, High-Throughput X-ray Observations

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Overview:

HEX-P is a probe-class mission concept that will combine high spatial resolution X-ray imaging (<10 arcsec FWHM) and broad spectral coverage (0.1-150 keV) with an effective area far superior to current facilities (including XMM-Newton and NuSTAR) to enable revolutionary new insights into a variety of important astrophysical problems.

- HEX-P is ideally suited to address important problems in the physics and astrophysics of magnetars and other young isolated neutron stars.
- For Fast Radio Bursts (FRBs), HEX-P will significantly expand our understanding in areas such as the coincidence of X-ray bursts along with FRBs, and the luminosity ratio L_R/L_X.
- For magnetars with persistent non-thermal emission, HEX-P will measure hard X-ray pulse profiles with sufficient statistics to constrain the particle Lorentz factor and system geometry.
- For transient magnetars, HEX-P's large effective area in the hard X-ray band will address the fundamental question of how long magnetospheric currents persist post-outburst.

More information on HEX-P, including the full team list, is available at hexp.org.

Magnetars

- Group of 26-confirmed isolated neutron stars with the strongest B-fields in the universe, often surpassing 10^{14} G.
- Primarily X-ray emitters, showing a bright hot (0.5 keV) thermal emission, likely from the surface, and unique non-thermal hard X-ray tails (photon index $\Gamma \sim 0$), sometime dominating the full SED. Both components are pulsating at the source' spin-period (Fig. 1).
- Notoriously variable over milliseconds to years time-scales. Over the latter, they show bright (up to 10^{41} erg), hard X-ray bursts, which can come in storms. At times of bursts, they typically enter outburst epochs, during which they show an increase to their quiescent X-ray flux, hardened X-ray spectra, altered pulse shape and fraction, and, glitch activity and timing noise. These last months to years.
- Few, 25% of the population, shows transient pulsar-like radio emission, and one, SGR 1935+2154, is the source of Fast Radio Bursts.

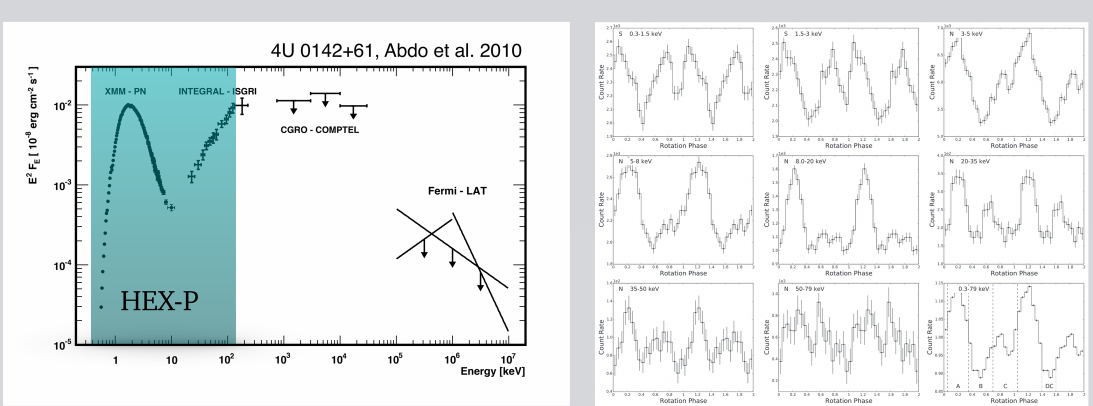

Fig. 1. *Left.* Broad-band X-ray spectrum of the magnetar 4U 0142+61 displaying the soft thermal-like shape and the dramatic turnover at 10 keV where the non-thermal emission dominates. *Right.* 4U 0142+61 energy-resolved pulse profiles from NuSTAR+XRT.

Hard X-ray tails discoveries

- Magnetar discovery is currently driven by Swift/BAT at a rate ~0.5 /yr.
- NuSTAR observations of 10 of these magnetars in quiescence revealed the hard X-ray tail emission, a sign of twists in the magnetosphere and particle acceleration. Fifteen confirmed magnetars lack a detection.
- Strength of this component typically correlates with the (spin-down) age of the source.
- eROSITA will undoubtedly find large numbers of magnetar candidates (e.g., Pires et al. 2017). **HEX-P follow-up will enable confirmation**.
- Radio surveys such as SKA will also unravel a population of radio-loud magnetars akin to 1E 1547.0-5418.
- **HEX-P will push the detection limit (>10σ) of magnetar hard X-ray tails by $\gtrsim$1 order of magnitude for a 100 ks observation (Fig. 2).**

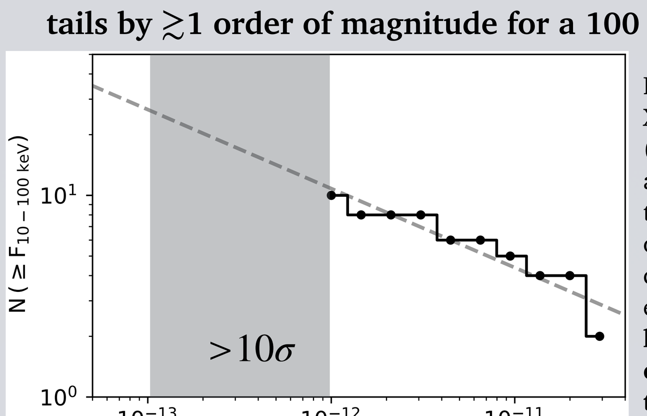

Fig. 2. LogN-logS of the current hard X-ray detections from magnetars (mainly from NuSTAR; black dots and histogram). HEX-P will extend the X-ray tail detectability by an order of magnitude below the current limit (based on a 100 ks exposure). **Number of detected hard X-ray tails will more than double. Establishing the shape of the logN-logS will inform on crustal B-field and twist evolution.**

Do you have ideas for how HEX-P would revolutionize your science? Get in touch!

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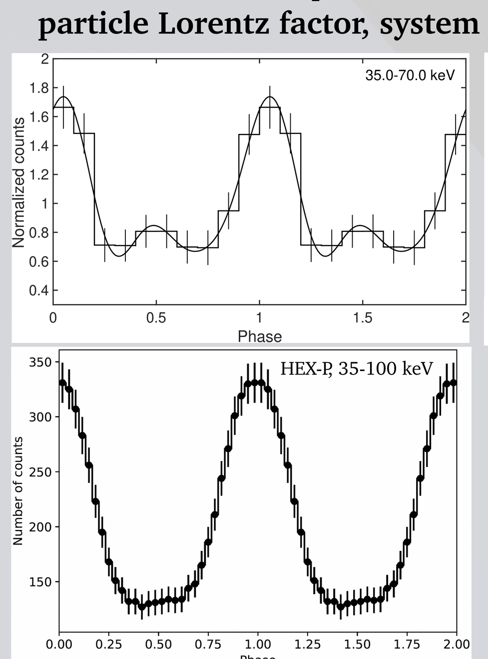
HEX-P
HIGH ENERGY X-RAY PROBE

Hard X-ray Pulse Profile constraints

- Hard X-ray tails in magnetars are likely the result of resonant inverse Compton scattering of hot surface thermal photons by relativistic electrons ($\gamma = 10 - 100$) in the magnetosphere.
- Exotic QED processes are operating in magnetar's B-field regime, e.g., photon splitting and single photon pair-creation (Wadiasingh 2019).
- Emission is strongly beamed along magnetic field lines, implying strong diagnostics on the geometries of these systems (Fig. 3).
- High S/N hard X-ray pulse profiles is required to confront models with data, not attained so far. **HEX-P will provide much improved statistics** to accomplish this task, **likely providing a constraint on particle Lorentz factor, system geometry, and twisted loop volume**.



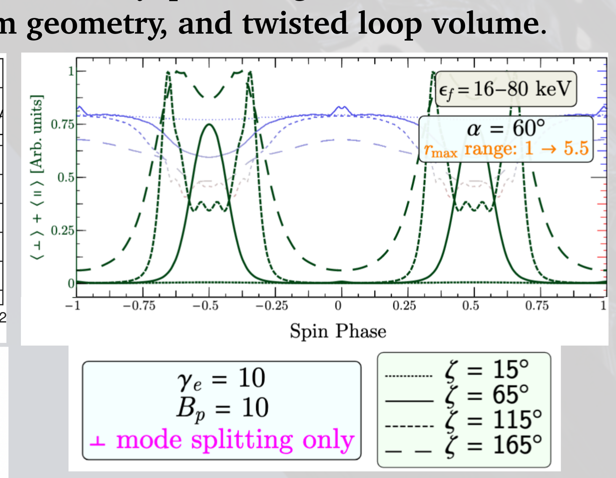


Fig. 3. *Upper-left.* NuSTAR 35-70 keV pulse profile of 1RXS J170849.0-400910 from a 100 ks exposure. *Lower-left.* HEX-P simulation of the same signal. *Right panel*. Theoretical predictions of hard X-ray light curves of total intensity (green curves) for different viewing geometries.

Fast Radio Bursts (FRBs)

- Magnetars are so far the only astrophysical sources unambiguously associated with Fast Radio Bursts (FRBs). The FRB, emitted by SGR 1935+2154, occurred during the most intense bursting episode of the source so far, and simultaneous to an X-ray burst (Bochenek et al. 2020, CHIME/FRB 2020, Li et al. 2021).
- Observationally, most, if not all, radio bursts occur at the time of X-ray bursts, though the opposite is certainly incorrect; the majority of X-ray bursts are radio silent.
- Broad-band spectral diagnostics indicate that the FRB-associated X-ray burst is softer yet possessing a higher energy cutoff (Fig. 4).
- HEX-P broad-band energy coverage (0.5-150 keV), large effective area, and low background implies a relatively complete coverage of magnetar bursts logN-logS (Fig. 4).
- **Observations of magnetars during burst-active episodes will enable answers to: 1) do faint FRB-like bursts also occur at times of X-ray bursts?, 2) is the spectral difference universal across radio fluence?, is L_R/L_X constant? The answers to these questions may lead to a deeper understanding of the magnetar FRB triggering local and radio/X-ray emission mechanism.**

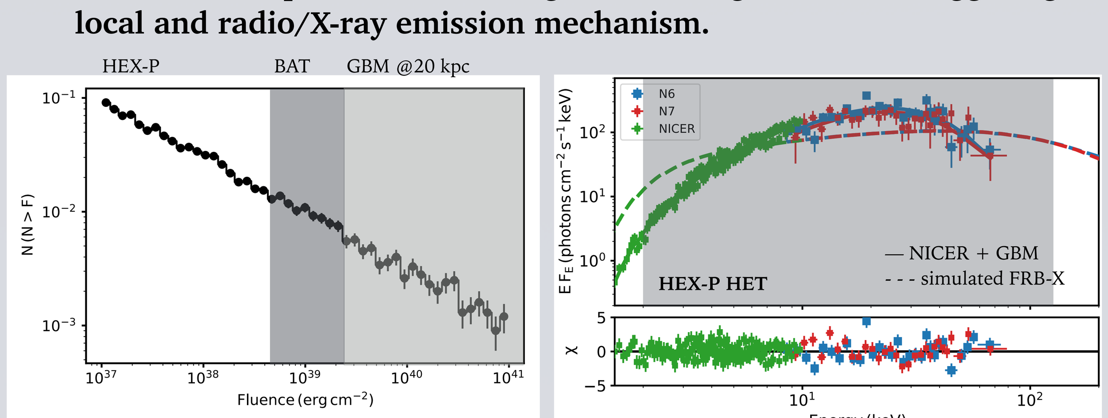


Fig. 4. *Left.* LogN-LogS of magnetar bursts. HEX-P will cover the faint end of the distribution up to the edge of the MW. *Right.* FRB-associated X-ray burst (dashed line) compared to a radio-silent X-ray burst with similar fluence (from Younes et al. 2021). Note the spectral extension in the latter. HEX-P broad energy coverage is ideal to constrain magnetar burst spectral curvature.

Tracking the Evolution of Magnetospheric Currents around Transient Magnetars

- How long the non-thermal emission persists is a fundamental open question about transient magnetar outbursts. Magnetar non-thermal emission originates from activated currents of particles flowing through the neutron star's magnetosphere. **HEX-P's large effective area and excellent angular resolution in the hard X-ray band are critical to understanding the physics of how a magnetar's magnetosphere relaxes back into a steady state following an outburst.**
- Here we have simulated NuSTAR and HEX-P observations of the April 2013 outburst of the transient magnetar in the galactic center region, SGR 1745-2900. (Top panel) Spectral parameters are shown in the table to the left of the spectrum (Mori et al. 2013).
- NuSTAR tracked SGR 1745-2900's hard X-ray emission for 4 months post-outburst (Kaspi et al. 2014). After this time, it became difficult to distinguish the fading hard X-ray flux from SGR 1745-2900 from the emission of other transient sources in the active, crowded galactic center region.
- Later observations of SGR 1745-2900's slow (> 6 yr.) decay from its outburst were performed, but only possible in the soft X-ray band thanks to the excellent angular resolution of Chandra (Rea at al. 2020). We simulate later observations with the flux of the non-thermal emission decreasing on an exponential timescale. HEX-P is uniquely suited to maintain good coverage of both the non-thermal and thermal emission long after the outburst.

Beginning of Outburst

Table 1
Spectral Modeling of the *Swift* and *NuSTAR* Data

Model	BB	BB+PL
N_{H} (10^{22} cm^{-2})	$12.98^{+0.54}_{-0.52}$	$14.20^{+0.71}_{-0.65}$
kT (keV)	1.000 ± 0.010	$0.956^{+0.015}_{-0.017}$
BB flux (erg cm^{-2} s^{-1})	$(4.39 \pm 0.04) \times 10^{-11}$	$(4.73 \pm 0.04) \times 10^{-11}$
BB luminosity (erg s^{-1})	...	$(3.62 \pm 0.03) \times 10^{35}$
BB radius (km)	...	1.7 ± 0.1
Γ	...	$1.47^{+0.46}_{-0.37}$
PL flux (erg cm^{-2} s^{-1})	...	$(6.22 \pm 0.57) \times 10^{-12}$
χ^2_r (dof)	1.44 (466)	1.01 (464)

Notes. N_{H} is the column density, kT is the temperature of the blackbody, and Γ is the photon index of the power law. The 2–79 keV fluxes are given for the individual components. The goodness of fit is evaluated by the reduced χ^2 and the degrees of freedom are given between brackets. The errors are 90% confidence ($\Delta\chi^2 = 2.7$). The blackbody radius is assuming a distance of 8 kpc.

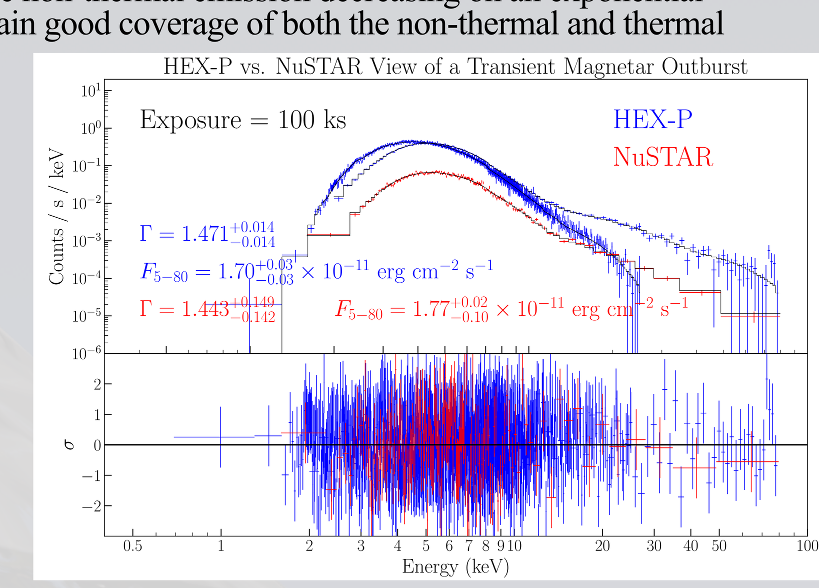


Fig. 5. Plot of the X-ray spectrum of SGR 1745-2900 at the beginning the April 2013 outburst.

Tracking the Post-Outbust Evolution

- After one decay timescale, HEX-P is still able to accurately measure the non-thermal flux and photon index. At this point the spectrum is not constrained by NuSTAR due its limited angular resolution. The hard X-ray emission at the this phase of the outburst will provide key information required to understand how a magnetar returns to a steady state post-outburst. Currently it is unknown if magnetospheric or subsurface currents are what power magnetar emission long after the flux has decayed from its peak luminosity.

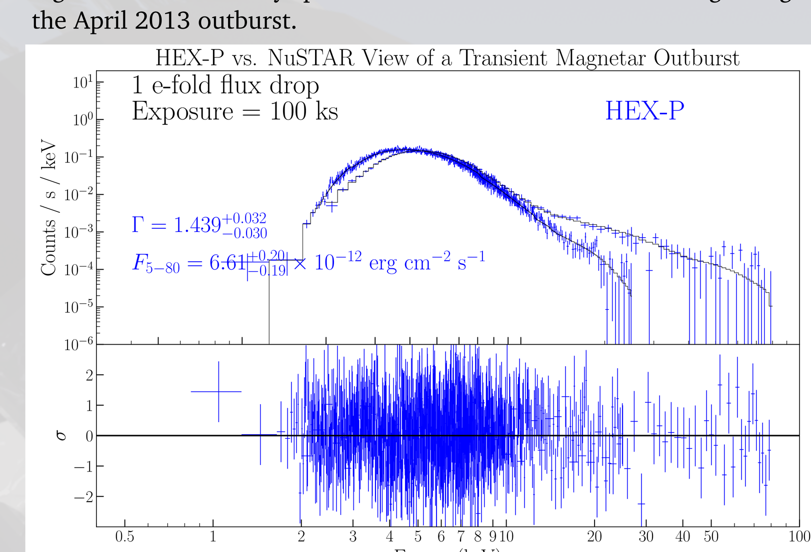


Fig. 6. Plot of the simulated X-ray spectrum of SGR 1745-2900 after its emission has decayed by a factor of e. The measurement is only possible with HEX-P's excellent angular resolution and large effective area.

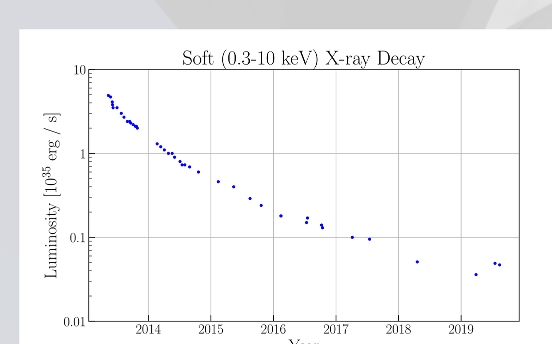


Fig. 7. Decay of the soft (0.3-10.0 keV X-ray luminosity of SGR 1745-2900 measured by Chandra over six years after the 2013 outburst (data points from Rea et al. 2020). HEX-P will allow us to produce a similar luminosity decay curve in the hard X-ray band during future outbursts.

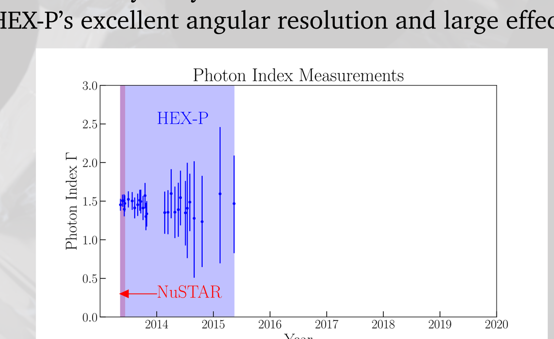


Fig. 8. Measurements of the hard X-ray photon index based on simulated HEX-P data, assuming the hard X-ray flux follows the decay of the soft X-ray flux shown in Figure 7. The blue shaded region indicates the time period when HEX-P can constrain the hard X-ray photon index, with the corresponding time period for NuSTAR shaded in red.

Expanding the Population of Known Magnetars

- In the 2030s, HEX-P could complement a variety searches for high-energy transients, and expand currently small group of only 26 confirmed isolated neutron stars with B-fields surpassing 10^{14} G.
- HEX-P's sensitivity in the hard X-ray band could be a critical component in searches seeking to identify and understand populations of fainter and/or more distant magnetars.
- Since most magnetars have been found in crowded regions of galactic plane; a high angular resolution may be critical to resolving new sources in these regions.

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