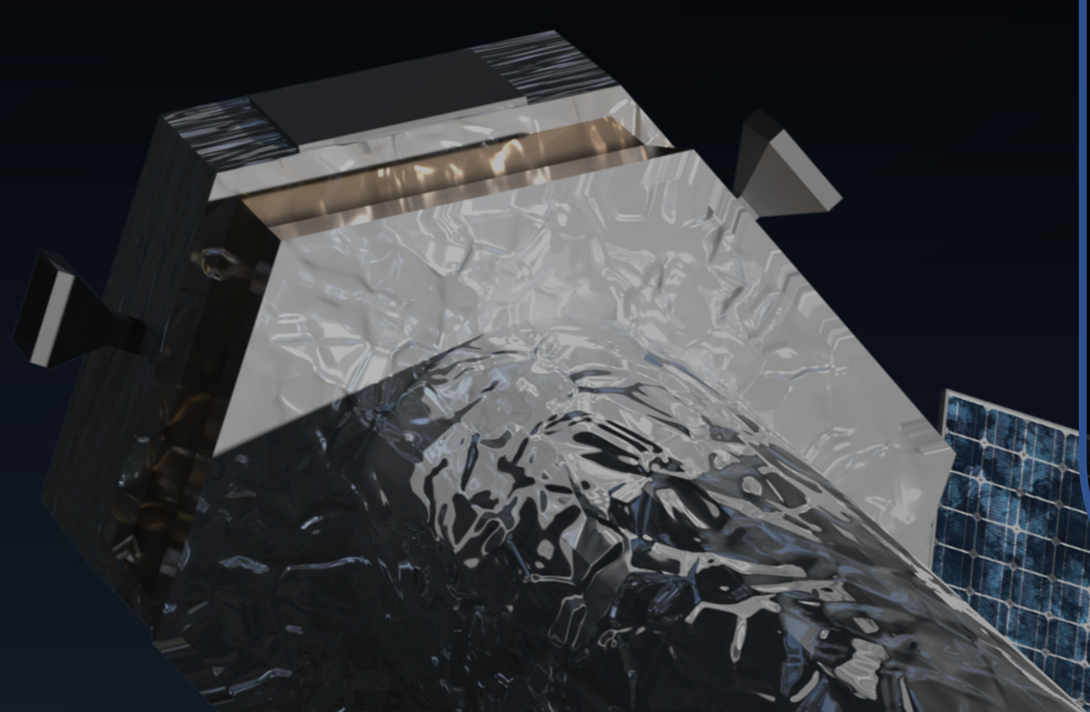

The High Energy X-Ray Probe (HEX-P)

Pulsar Monitoring, Timing and Searches using Broadband X-ray Emission

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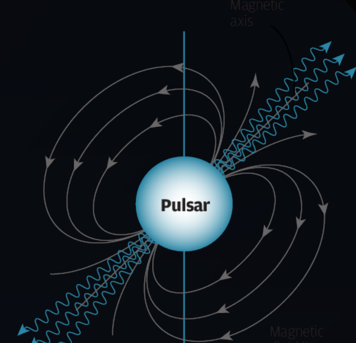
Overview:

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. We present simulations of HEX-P's ability of detecting and hence timing millisecond pulsars over a range of luminosity ranges. HEX-P would allow us to find new pulsar systems including in the crowded environments and enable the study of geometry and energetics of intra-binary shocks in pulsar binaries allowing for a deeper understanding of particle acceleration, companion ablation and orbital evolution of pulsar binaries. More information on HEX-P, including the full team list, is available at https://hexp.org.

Pulsars

Most neutron stars are observed as pulsars. In a simplistic model of pulsar emission, plasma flows along the open field lines, and photons emitted in a direction tangential to this flow generate beamed electromagnetic radiation. The misalignment of the magnetic and rotational axes of a pulsar causes the beamed energetic emission to sweep past an observer's line-of-sight at the frequency of pulsar rotation. Each time this occurs, an intense pulse is registered in observer's detectors. We stack these individual pulses appropriately to obtain a high SNR pulsar profile which characterizes a given pulsar.



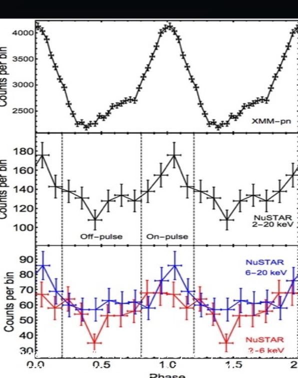
Nearly 3350 pulsars over a range of spin periods have been discovered with various radio, γ-ray and X-ray telescopes.

- Of this population, approximately ~15% are millisecond pulsars (MSPs) with periods less than twenty milliseconds.
- More than half of the MSPs are found in binaries with companion stars.
- 25% of the MSPs both in galactic field and globular clusters have associated X-ray emission.

MSPs, through their X-ray emission, have wide ranging applications such as constraining neutron star equations of state, providing gravitational wave merger rates by informing us of the diverse formation channels for neutron star systems, and refining pulsar emission theories. Rigorous statistical analysis of spectral and timing properties of diverse MSP populations can significantly impact our understanding of these fundamental questions.

Pulsed Thermal X-ray emission

Most of the observed MSPs are thermally dominated with surface X-ray emission limited to a small region (radius << R_{NS}) closer to the magnetic polar caps. The X-ray emission likely originates from return current heating of the polar caps. Such an effect is most prominent in rapid and recycled millisecond pulsars (Harding and Muslimov, 2001).



and pulse fraction diminish with increasing energy.

The X-ray pulsations observed in these systems are broadband with large duty cycles. Modelling these X-ray pulsations can help constrain mass and radius of the neutron star, and hence the equation of state of dense nuclear matter. Such an approach of constraining mass and radius of rotationally powered neutron stars through their stable, pulsed thermal emission is unaffected by temporal variabilities observed in accreting or oscillating pulsar systems.

We simulate HEX-P's ability to observe such pulsars by using 5.6ms PSR J0437−4715 whose X-ray emission can be characterized by thermal components and a non-thermal tail. In NuSTAR observations of the source pulsation significance and pulse fraction were observed to be energy dependent. (Guillot et al 2016). In HEX-P simulations we see at least a factor of 4 improvement in the source photon count, which would allow us to probe pulse profile variability and spectral modelling in greater details to strongly constrain the the M-R relationship for neutron stars.

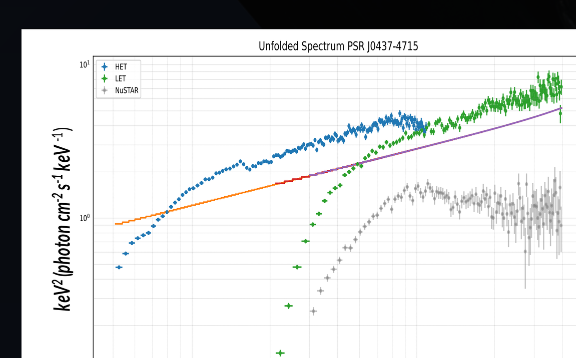


Figure c: Comparison of HEX-P HET, HEX-P LET and the NuSTAR spectra for an observation duration of 50 ks. The PSR J0437-4715 spectrum is modelled with two blackbody and a powerlaw component.

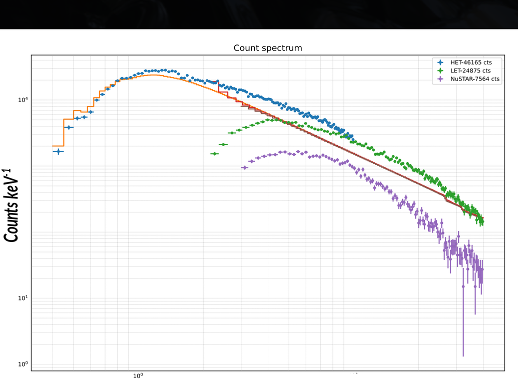


Figure c: Counts spectrum per keV for HEX-P HET, LET and NuSTAR. Legend contains information on total counts expected from PSR J0437-4715 with each detector in a 50 ks observation.

Pulsed Non-Thermal X-ray Emission

A subgroup of MSPs emit pulsed non-thermal X-ray emission which can be attributed to the radiation from the pulsar magnetosphere. In these systems the pulsations are usually observed to be peaked with narrow pulse profiles and short duty cycles. Moreover, the pulse profiles are usually asymmetric.

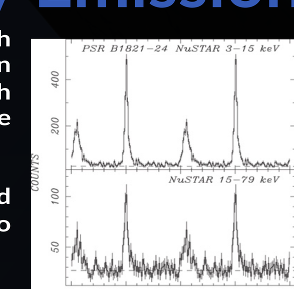


Figure a: Hard X-ray profiles for non-thermally emitting PSR B1821-24 in two X-rays bands. The significance of pulse profiles in hard X-ray band is impacted by scarcity of photons.

The spectra of the pulsed X-ray emission can usually be well-described by a power law and is observed to extend into hard X-ray band up to 79 keV with no turnover (Gothelf and Bogdanov 2017).

Most of the observed non-thermally emitting MSP systems are relatively young and energetic with high magnetic fields at the light cylinder radius compared to their MSP counterparts. The X-ray emission itself is theorized to originate from relativistic acceleration of particles in the pulsar magnetosphere akin to younger pulsar systems. Extending the pulsar spectral and timing analysis for these systems to hard X-ray bands can provide crucial information to understand magnetospherically driven pulsar emission processes.

In our simulations we find that HEX-P would be able to detect such systems at a magnitude lower X-ray flux than current hard X-ray observatories, and with a significantly higher photon yield (see, Fig. below). This would allow us to probe variations in pulse profiles of non-thermally pulsating neutron stars at higher energies. It would also allow us to understand if there might be a spectral cutoff at higher energies which would help constrain emission theories.

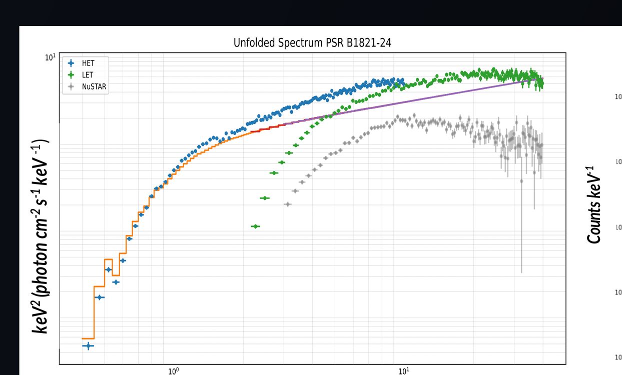


Figure c: Comparison of HEX-P HET, HEX-P LET and the NuSTAR spectra for an observation duration of 50 ks and at a source flux level of 2.2 e^{-12} ergs $cm^{-2}s^{-1}$. We assume absorbed power law model with neutral Hydrogen density of 0.401e^{22} and Γ=1.28.

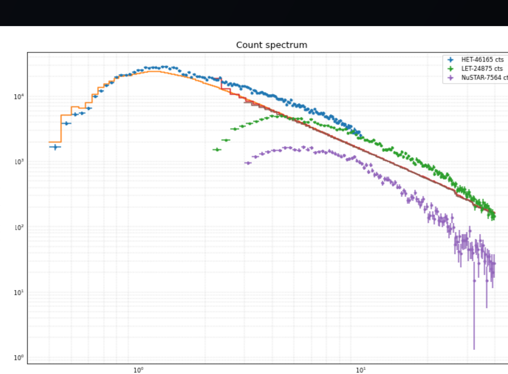


Figure c: Counts spectrum per keV for HEX-P HET, LET and NuSTAR. Legend contains information on total PST B1821-24 counts expected for each detector in a 50 ks observation.

X-ray Emission from the Intra-binary Shock (IBS)

In MSP binaries such as spider binaries (low mass companions, tight binary orbits with Pb<1 day), the pulsar wind collision with radiatively driven winds from the companion produces an intra-binary shock (IBS). The IBS is the site of production of un-pulsed, non-thermal emission. The observed X-ray luminosity is low $L_x \approx 10^{30\text{-}33}$ erg s^{-1}, and the X-ray emission extends up to from 0.3 keV to harder X-ray bands with a spectral index of, $\Gamma \leq 1.5$ (Roberts et al. 2015). Additionally, the X-ray emission is observed to be modulated at the binary phase (Romani and Sanchez 2016, Wadiasingh 2017, An 2019). Broadband X-ray observations with HEX-P of the IBS in various MSPs will help us resolve geometry and energetics of the wind collision.

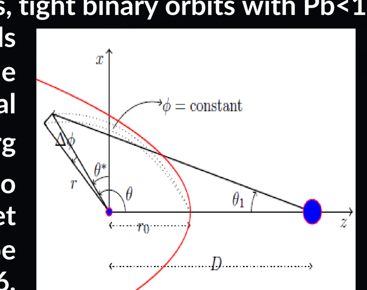


Figure a: Basic geometry of the intra-binary shock.

A) Spectral cutoff

If IBS electrons are accelerated to the radiation reaction limit, the synchrotron (SY) emission cutoff of the IBS is expected at E$\leq$ 100 MeV. In this case, a cooling break would appear at ~MeV and not be measurable with current X-ray observatories.

However, the IBS acceleration may not be very efficient, and a cutoff may be present at a lower energy (no significant cooling; right- bottom figure). Then, a measurement of a spectral cutoff can thus tell us the maximum energy of the accelerated particles (shock acceleration)

Can HEX-P detect a spectral cutoff?

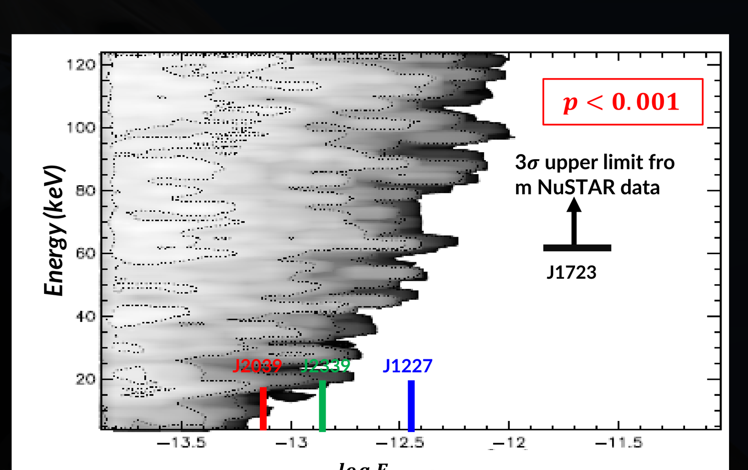


Figure b : XSPEC simulation for a Γ=1.28 power law (phase averaged; measured for J1723) with an exponential cut off at the energy, E_break.

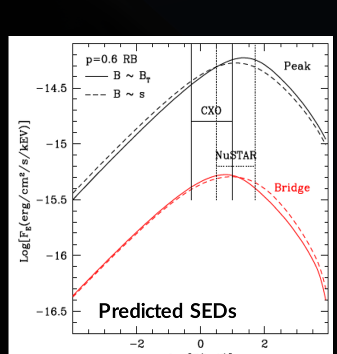
Simulation for exposure of 100 ks with radii R=10'' for the source and R=30'' background extraction.

White regions are part of the parameter space that HEX-P can probe. Three vertical dashes show flux levels for three known MSP systems PSR J2039-5617, PSR J2339-0533 and PSR J1227-4859.

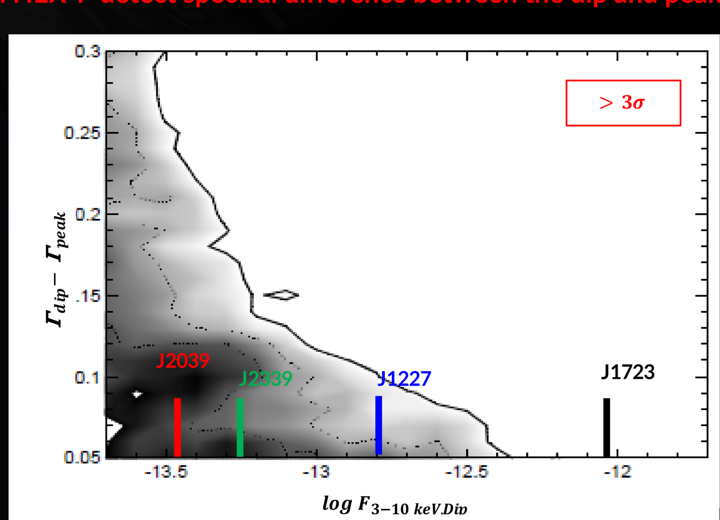
B) Spectral difference between the dip and peak

The orbitally-constant (dip) emission is composed of the pulsar blackbody + IBS emission of electrons with bulk Γ (Doppler boost) = 1 .

The modulated X-ray emission (peak) is thought to be produced by IBS electrons with bulk $\Gamma \geq 1$. The SY spectrum is shifted in energy by a factor of Γ, and so an X-ray observatory would see different part of the SY spectrum (right) with the modulating emission being harder even if the underlying emission spectrum is the same between the dip and peak.



Can HEX-P detect spectral difference between the dip and peak phases?



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

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HIGH ENERGY X-RAY PROBE

References:

1. Bogdanov, S., The Astrophysical Journal, vol. 887, no. 1, 2019. doi:10.3847/2041-8213/ab53eb.
2. Guillot, S., Monthly Notices of the Royal Astronomical Society, vol. 463, no. 3, pp. 2612–2622, 2016. doi:10.1093/mnras/stw2194.
3. Harding, A. K. and Muslimov, A. G., The Astrophysical Journal, vol. 556, no. 2, pp. 987–1001, 2001. doi:10.1086/321589.
4. Gotthelf, E. V. and Bogdanov, S., The Astrophysical Journal, vol. 845, no. 2, 2017. doi:10.3847/1538-4357/aa813c.
5. Romani, R. W. and Sanchez, N., The Astrophysical Journal, vol. 828, no. 1, 2016. doi:10.3847/0004-637X/828/1/7.
6. Wadiasingh, Z., Harding, A. K., Venter, C., Böttcher, M., and Baring, M. G, The Astrophysical Journal, vol. 839, no. 2, 2017. doi:10.3847/1538-4357/aa69bf.
7. An, H., Romani, R. W., and Kerr, M., The Astrophysical Journal, vol. 868, no. 1, 2018. doi:10.3847/2041-8213/aaedaf.