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NuSTAR observations of three young pulsars and their nebulae

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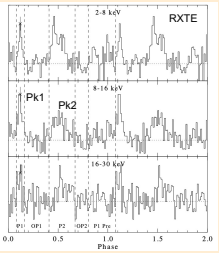
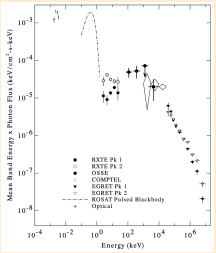
Abstract: We report the results of NuStar observations of 3 young and energetic pulsars (Vela, PSR J1101-6101, and J1617-5055) which, nonetheless, exhibit quite different observational properties across the electromagnetic spectrum. Two of these pulsars are often dubbed MeV pulsars while Vela is a bright gamma-ray and radio pulsar. We present the energy-resolved lightcurves, phase resolved spectra, and also examine the pulsar-wind nebulae (PWNe) properties for Vela and PSR J1101-6101.

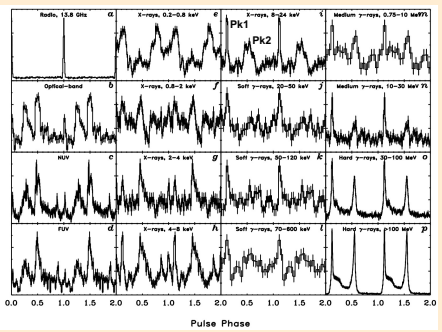
Vela pulsar

- Vela pulsar (B0833-45) is a nearby (d≈300 pc), 11-kyr-old pulsar located inside Vela SNR.
- It has period of 89 ms and the spin-down energy loss rate $E = 6.9\times10^{36}$ ergs/s.
- The X-ray spectrum of Vela pulsar is mostly thermal <2 keV and nonthermal >3 keV.
- The pulsar is one of the brightest objects on the sky in GeV gamma rays
- This NuSTAR observation is the first hard X-ray imaging observation where the Vela PWN is resolved.
- Pulsar is much fainter compared to PWN (see the CXO image below; it contributes about 4%-5% of total counts in 3-8 keV). It only makes small contribution into the total spectrum extracted from r=50″ aperture. The contribution is even smaller off-pulse.
- Conversely, the pulsar spectrum is strongly contaminated by the PWN in NuSTAR data. Pulsed emission contribution is maximized in r=50″ aperture.
- The pulsar itself has been previously studied in hard X-rays with RXTE and INTEGRAL (Strickman et al. 1999; Kuiper & Hermsen 2015; Mattana et al. 2011).

Previous hard X-ray observations of the Vela pulsar.

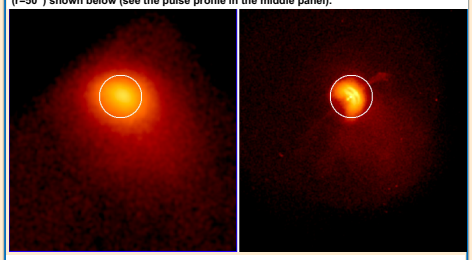




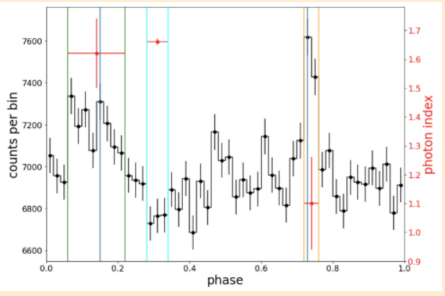


Based on RXTE data analysis the photon indices for Peak 1 and Peak 2 are , $\Gamma_1 = 0.68 \pm 0.14$ and $\Gamma_2 = 1.17 \pm 0.12$, respectively. The fit quality was not very good. (See Strickman et al. 1999 for details).

Pulsar contribution is reduced but taking only off-pulse events from the circular region (r=50″) shown below (see the pulse profile in the middle panel).



The white circles (r=50″) shows the extraction area for the spectral fits (below) and for the pulse profile (shown in the middle).



We fitted Peak 1 and Peak 2 spectra using the spectrum from the Off-Pulse interval as a background. Although Pk1 spectrum is substantially harder than Pk2 spectrum (in qualitative agreement with Strickman et al. 1999), the actual best fit values are different: Peak 1 $\Gamma_1 = 1.10 \pm 0.15$, and Peak 2 $\Gamma_2 = 1.62 \pm 0.20$.

These values are substantially smaller than in the earlier RXTE results.

The photon index value for the harder Peak 1 spectrum is comparable to those for the hardest inner regions of the Vela PWN (as determined from CXO fits) – the inner jets. A coincidence?

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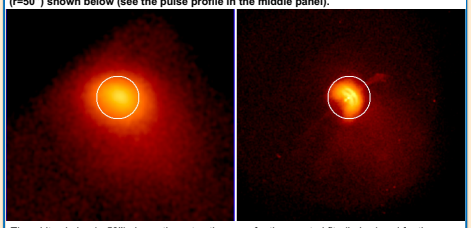
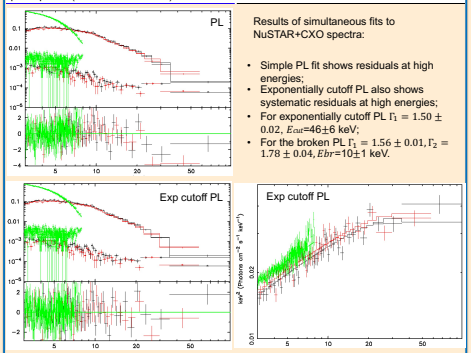
Vela PWN

Pulsar contribution is reduced but taking only off-pulse events from the circular region (r=50″) shown below (see the pulse profile in the middle panel).

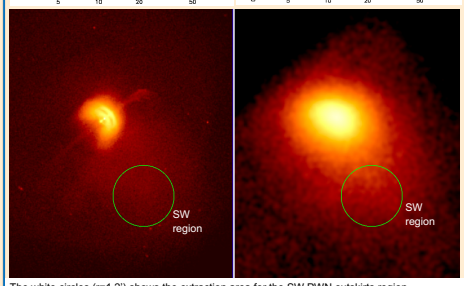


The white circles (r=50″) shows the extraction area for the spectral fits (below) and for the pulse profile (shown in the middle).

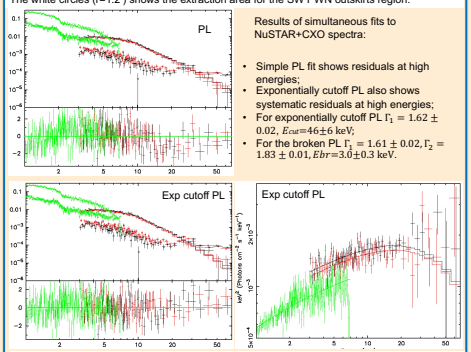


Results of simultaneous fits to NuSTAR+CXO spectra:

- Simple PL fit shows residuals at high energies;
- Exponentially cutoff PL also shows systematic residuals at high energies;
- For exponentially cutoff PL $\Gamma_1 = 1.50 \pm 0.02$, E_{cut}=46±6 keV;
- For the broken PL $\Gamma_1 = 1.56 \pm 0.01$, $\Gamma_2 = 1.78 \pm 0.04$, Ebr=10±1 keV.



The white circles (r=1.2′) shows the extraction area for the SW PWN outskirts region.



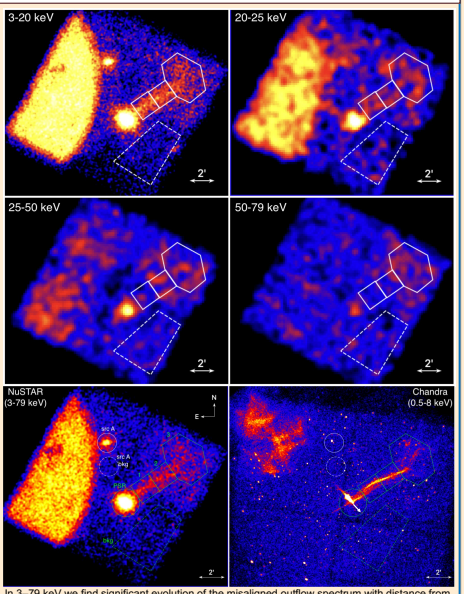
Results of simultaneous fits to NuSTAR+CXO spectra:

- Simple PL fit shows residuals at high energies;
- Exponentially cutoff PL also shows systematic residuals at high energies;
- For exponentially cutoff PL $\Gamma_1 = 1.62 \pm 0.02$, E_{cut}=46±6 keV;
- For the broken PL $\Gamma_1 = 1.61 \pm 0.02$, $\Gamma_2 = 1.83 \pm 0.01$, Ebr=3.0±0.3 keV.

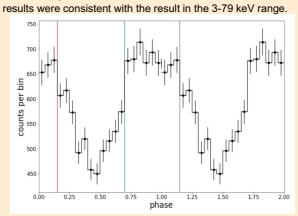
- **Although fits to the CXO+NuSTAR spectra for the compact PWN and the SW outskirts region suggest that spectrum might be more complex than a simple PL, the evidence for an exponential cutoff is lacking (especially for the SW region). This implies particle energies of about 0.2 PeV which is about 4% of the total available potential drop for the Vela pulsar.**
- **In the absence of in-situ acceleration, particles must be transported to the SW region either by a bulk flow with an average velocity of >0.03c or via a simple kinetic diffusion consisted with Bohm diffusion (i.e. it is fast enough; cf. Porth et al. 2016).**

PSR J1101–6101 and the Lighthouse Nebula

- **PSR J1101-6101 is a midle-aged (116-kyrs), fast-moving pulsar with remarkable PWN (Lighthouse). PWN consists of small bright compact nebula and large-scale misaligned outflow orthogonal to the apparent pulsar's velocity direction.**
- **It has period of 83 ms and the spin-down energy loss rate $E = 1.4\times10^{36}$ ergs/s.**
- **PSR J1101-6101 is one of the so-called MeV pulsars, it is radio and gamma-ray quiet.**
- **In the CXO energy range (0.5-8 keV) the bright compact PWN is much softer than the pulsar which helps to measure the pulsar spectrum at higher energies even though the pulsar cannot be resolved form the compact PWN with NuSTAR.**



In 3–79 keV we find significant evolution of the misaligned outflow spectrum with distance from the pulsar, with the spectral slope changing from $\Gamma_1 = 1.79 \pm 0.08$ to $\Gamma_3 = 2.21 \pm 0.08$ (in segments 1 and 3, respectively; see the above figure). To verify that our results were not skewed by the higher energy bins (in which the source count rates become progressively lower and in which the cosmic X-ray background becomes increasingly higher), we restricted the NuSTAR fits to the 3–20 keV range. We obtained $\Gamma_1 = 1.81\pm0.08$, $\Gamma_2 = 2.08\pm0.09$, and $\Gamma_3 = 2.31\pm0.08$; thus, these results were consistent with the result in the 3-79 keV range.

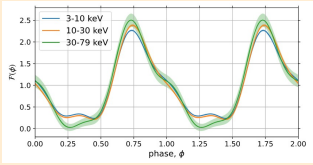


J1101 pulse profile in the 3-40 keV energy range. The red line shows the start of the phase range used for pulse minimum, which extends to the first blue line. Beyond the first blue line (at φ = 0.70) up until the second blue line corresponds to the phase range used for pulse maximum.

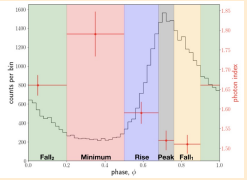
For the phase-resolved spectral analysis we chose two phase bins corresponding to the pulse maximum (from 0 < φ_{max} < 0.15 and 0.7 < φ_{max} < 1.0) and minimum (0.15 < φ_{min} < 0.70). Fitting the spectra from both phase ranges with an absorbed PL model we found $\Gamma_{max} = 1.11 \pm 0.05$ ($\chi2$ = 77/85 d.o.f.) and $\Gamma_{min} = 1.18 \pm 0.07$ ($\chi2$ = 59/70 d.o.f.) which are consistent with each other within their uncertainties..

PSR J1617-5055

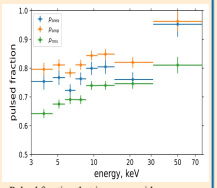
- **PSR J1617-5055 is a young (9-kyr) and energetic pulsar with underluminous PWN.**
- **It has period of 69 ms and the spin-down energy loss rate $E = 1.6\times10^{37}$ ergs/s.**
- **PSR J1617-5055 is one of the so-called MeV pulsars, it is radio and gamma-ray quiet.**



Normalized pulse profiles for several energy bands. All profiles are corrected for background. Shaded areas correspond to ±1 standard deviation.



We fit phase-resolved NuSTAR spectra with an absorbed power-law model in five phase bins and find that the photon index varies with phase from Γ = 1.52 ± 0.03 at phases around the flux maximum to Γ = 1.79 ± 0.06 around the flux minimum



Pulsed fraction that increases with energy. Three different commonly used definitions of pulsed fraction are shown in the figure.

See Hare et al. (2021) for details.

References: Strickman, M., Harding, A., & de Jager, O. 1999, ApJ, 524, 373 ■ Kuiper, L. & Hermsen, W. 2015, MNRAS, 449, 3827 ■ Mattana, F., et al. 2011, ApJ, 743, L18 ■ Porth, O. et al. 2016, MNRAS 460, 4135 ■ Hare, J., et al 2021, ApJ, 923, 249