Hard X−Ray Observations of the Redback PSR J1628−3205

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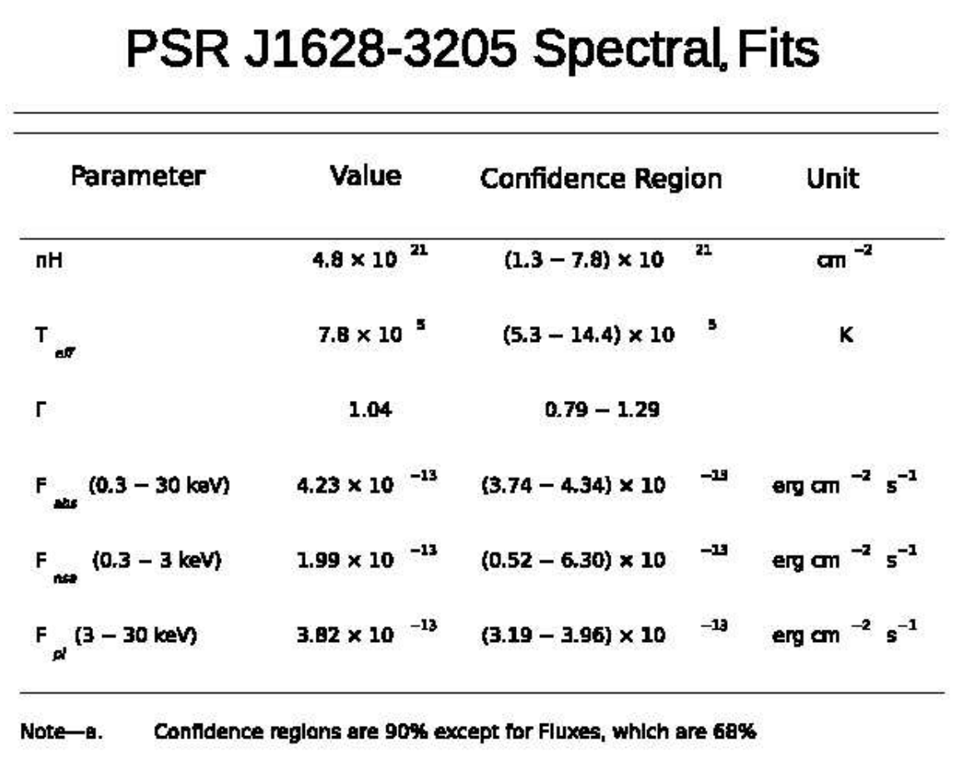
Abstract

We report on NuStar and Chandra X-Ray observations of the PSR J1628-3205 redback system. The hard X-ray emission is similar to other redbacks in having orbital modulation centered around pulsar inferior conjunction, a spectrum that is too hard for standard Fermi shock acceleration suggesting acceleration through magnetic reconnection with some softening further away from inferior conjunction. Looking at the 8 redbacks which have been observed by NuStar, there is an indication of softer spectra the more distant the shock is in terms of pulsar light cylinder radii. This may be due to partial dissipation of the magnetically dominated striped wind before the shock, leading to a mix of reconnection and Fermi shock acceleration. Under this hypothesis, we use the X-ray data to make empirically derived estimates of the dissipation radius for magnetically striped pulsar winds.

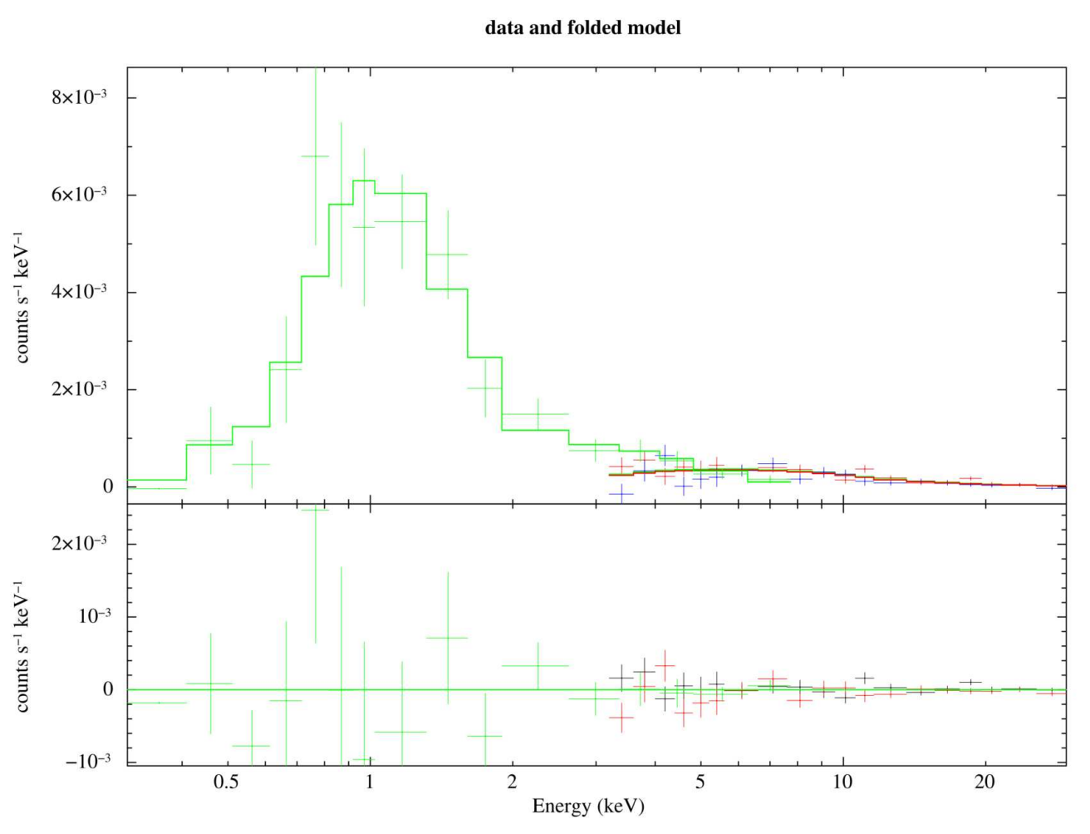
NuStar + Chandra Spectrum
NSA + Power Law



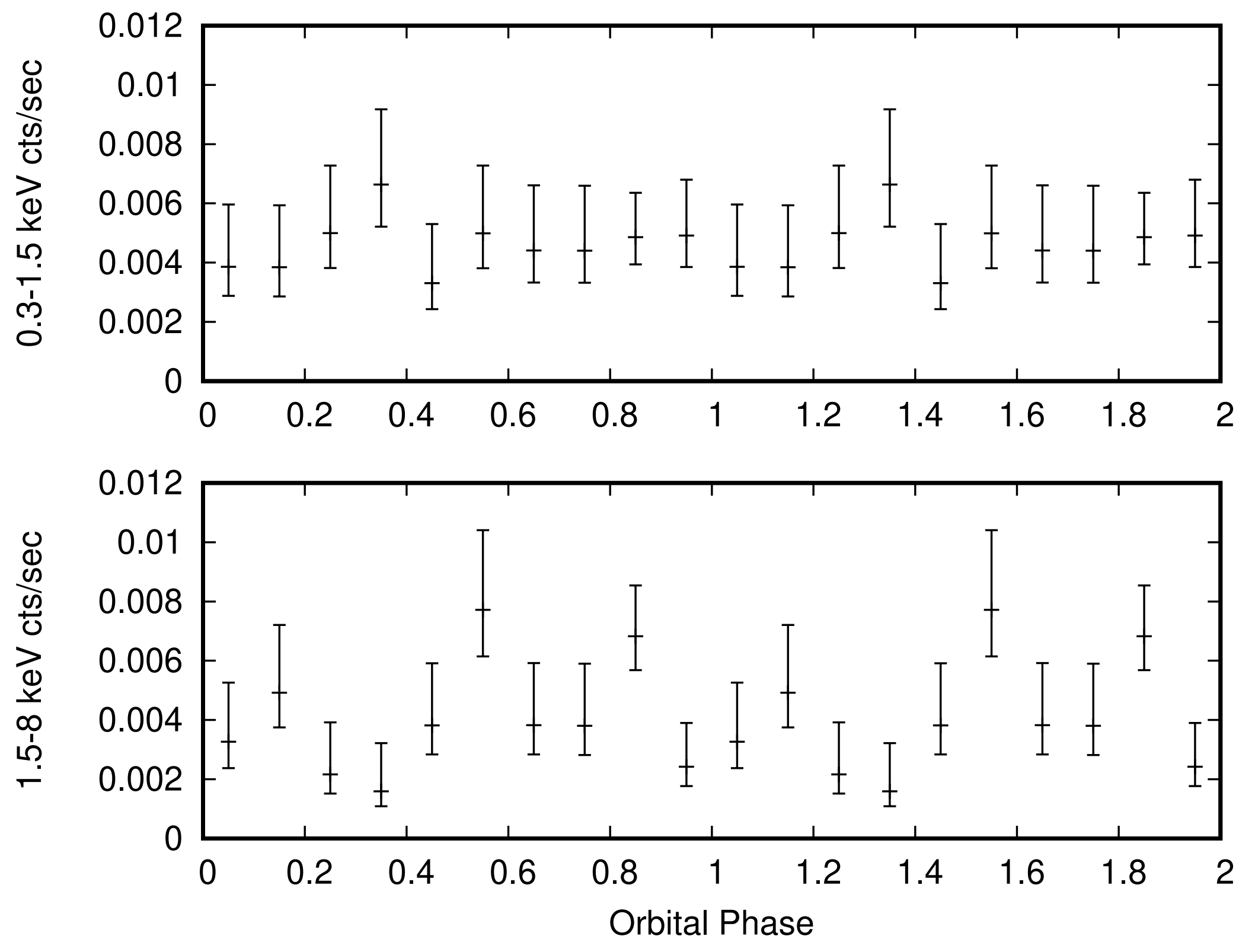
PSR J1628-3205 Spectral, Fits

Parameter	Value	Confidence Region	Unit
nH	4.8×10^{21}	$(1.3 - 7.8) \times 10^{21}$	cm^{-2}
T_{eff}	7.8×10^{5}	$(5.3 - 14.4) \times 10^{5}$	K
Γ	1.04	0.79 − 1.29	
F_{abs} (0.3 − 30 keV)	4.23×10^{-13}	$(3.74 - 4.34) \times 10^{-13}$	erg cm^{-2} s^{-1}
F_{nsa} (0.3 − 3 keV)	1.99×10^{-13}	$(0.52 - 6.30) \times 10^{-13}$	erg cm^{-2} s^{-1}
F_{pl} (3 − 30 keV)	3.82×10^{-13}	$(3.19 - 3.96) \times 10^{-13}$	erg cm^{-2} s^{-1}

Note—a. Confidence regions are 90% except for Fluxes, which are 68%

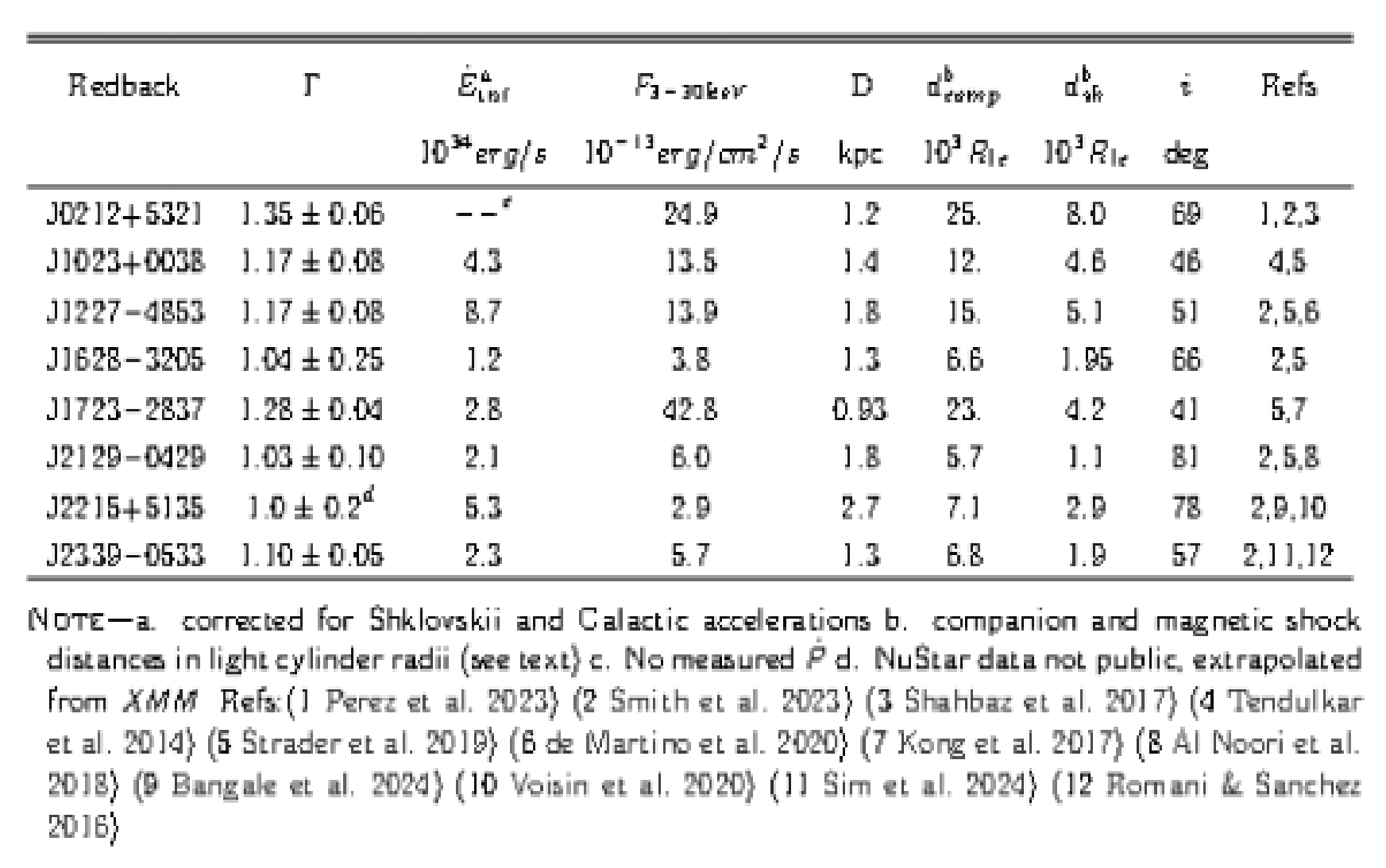


Chandra Observation



NuStar Redbacks

Redbacks systems consist of a millisecond pulsar in a tight orbit around a non-degenerate companion (Roberts 2010,2011,2013). They generally exhibit evidence of an intrabinary shock in the form of orbitally modulated hard (Γ = 1 – 1.5) X-ray emission centered around pulsar inferior conjunction (Roberts et al. 2015). 8 have now been observed by NuStar, all showing simple power law spectra out to at least 30 keV. Particle in Cell simulations suggest forced magnetic reconnection, implying a magnetically dominated wind, can produce spectra with Γ~1 (Cortes & Sironi 2022) while second order Fermi acceleration, implying a particle dominated wind, produces spectra with Γ~1.5. Where the pulsar magnetic wind energy dissipates and the wind energy becomes particle dominated has been an open question in pulsar research for decades (Cerutti et al. 2020).



Redbacks Observed by NuStar

Redback	Γ	$\dot{E}^{a}_{int}$	$F_{3-30keV}$	D	d^{b}_{comp}	d^{b}_{sh}	i	Refs
		10^{34}erg/s	10^{-13}erg/cm²/s	kpc	$10^3 R_{lc}$	$10^3 R_{lc}$	deg	
J0212+5321	1.35 ± 0.06	$--^{c}$	24.9	1.2	25.	8.0	69	1,2,3
J1023+0038	1.17 ± 0.08	4.3	13.5	1.4	12.	4.6	46	4,5
J1227−4853	1.17 ± 0.08	8.7	13.9	1.8	15.	5.1	51	2,5,6
J1628−3205	1.04 ± 0.25	1.2	3.8	1.3	6.6	1.95	66	2,5
J1723−2837	1.28 ± 0.04	2.8	42.8	0.93	23.	4.2	41	5,7
J2129−0429	1.03 ± 0.10	2.1	6.0	1.8	5.7	1.1	81	2,5,8
J2215+5135	1.0 ± 0.2^{d}	5.3	2.9	2.7	7.1	2.9	78	2,9,10
J2339−0533	1.10 ± 0.05	2.3	5.7	1.3	6.8	1.9	57	2,11,12

Note—a. corrected for Shklovskii and Galactic accelerations b. companion and magnetic shock distances in light cylinder radii (see text) c. No measured $\dot{P}$ d. NuStar data not public, extrapolated from *XMM* Refs:(1 Perez et al. 2023) (2 Smith et al. 2023) (3 Shahbaz et al. 2017) (4 Tendulkar et al. 2014) (5 Strader et al. 2019) (6 de Martino et al. 2020) (7 Kong et al. 2017) (8 Al Noori et al. 2018) (9 Bangale et al. 2024) (10 Voisin et al. 2020) (11 Sim et al. 2024) (12 Romani & Sanchez 2016)

References and Acknowledgements

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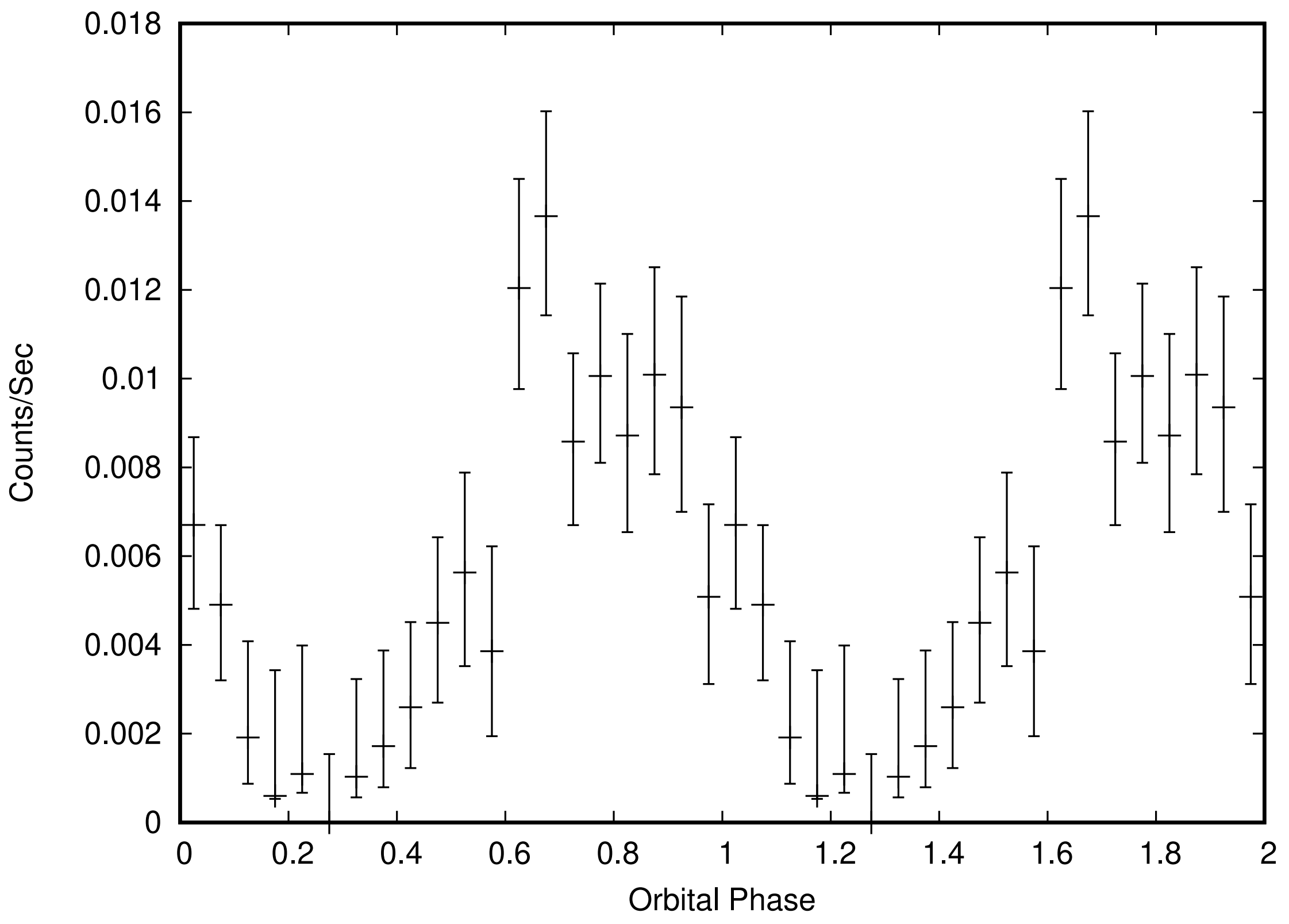
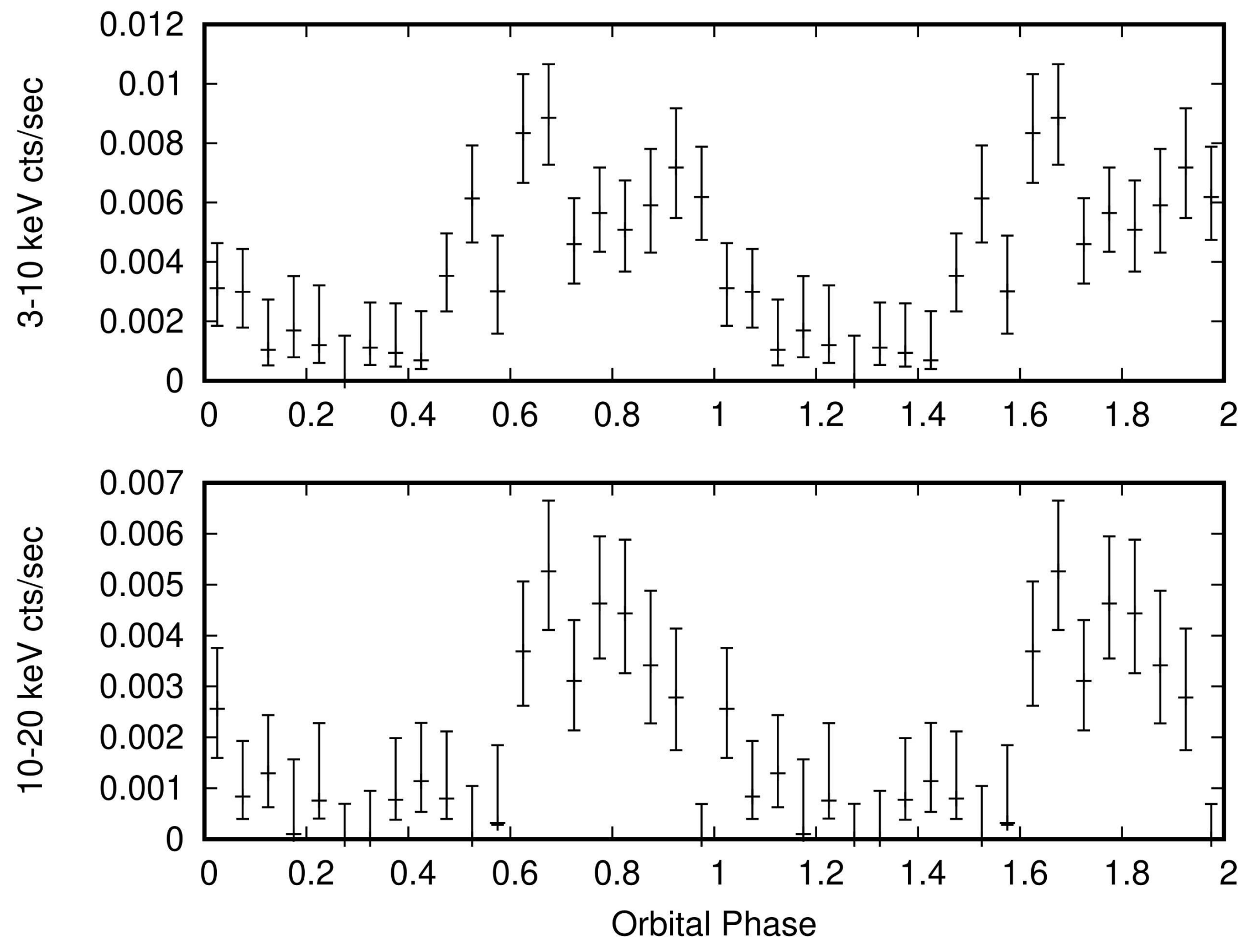
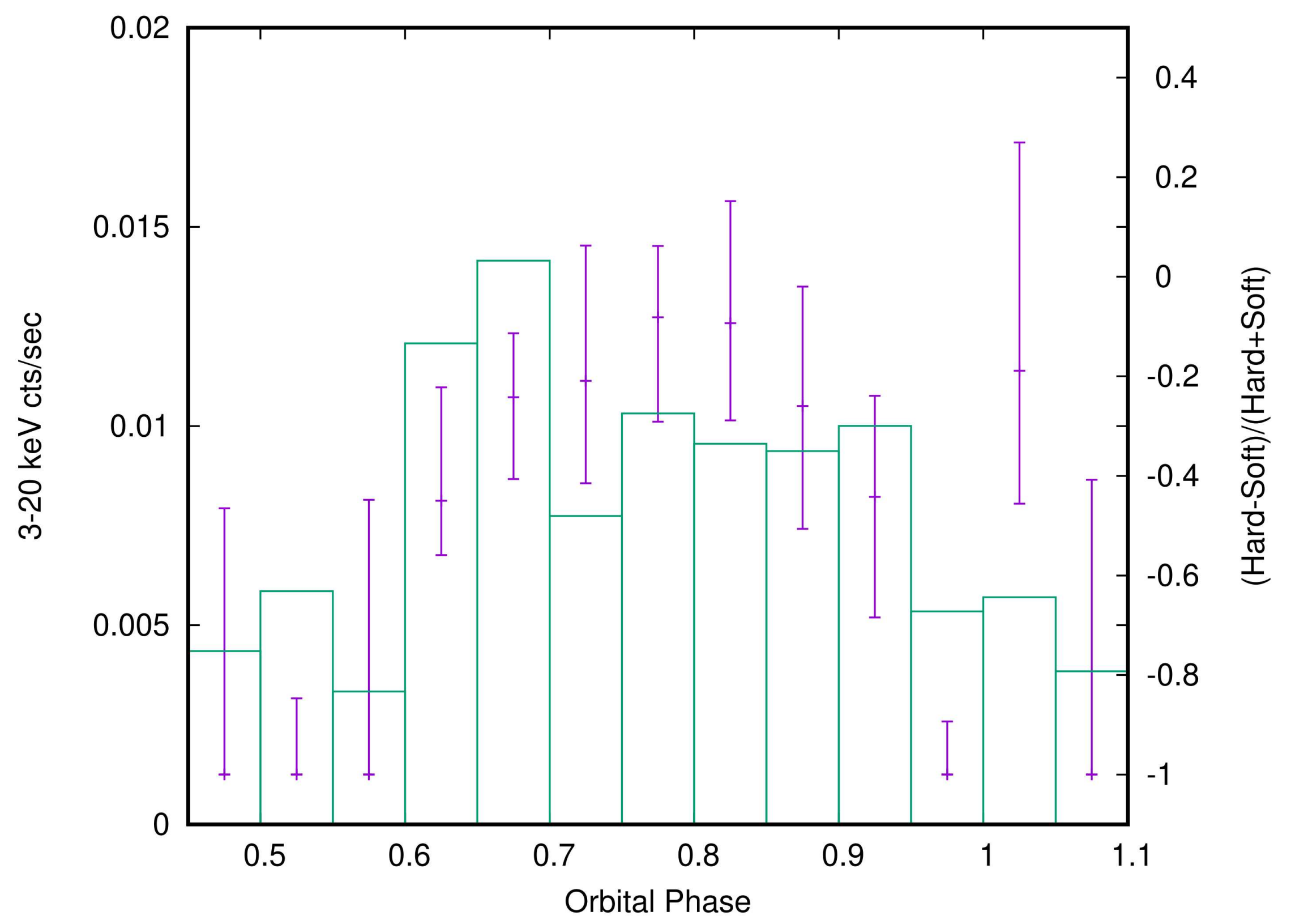
NuStar Observation



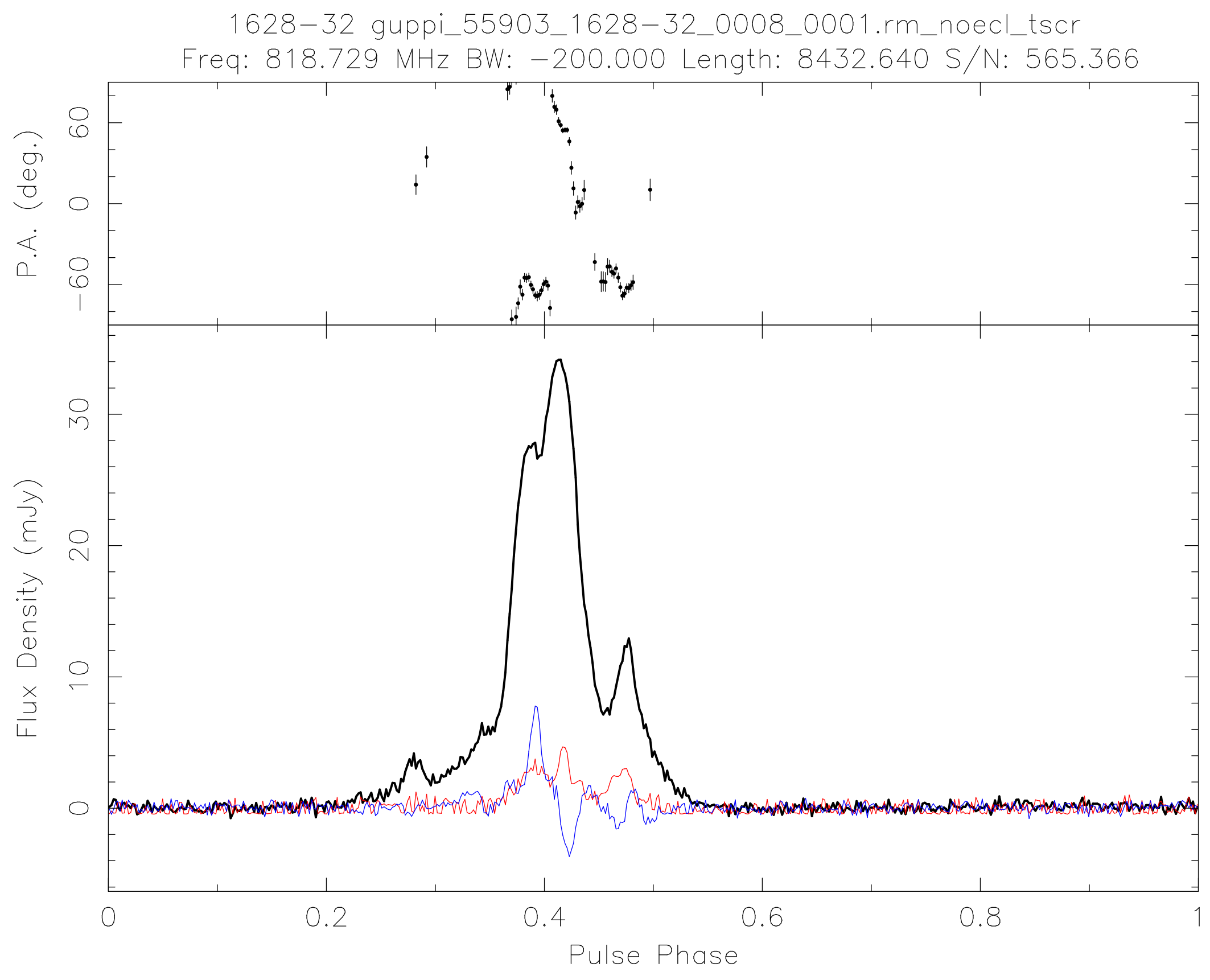
3−20 keV Folded Lightcurve



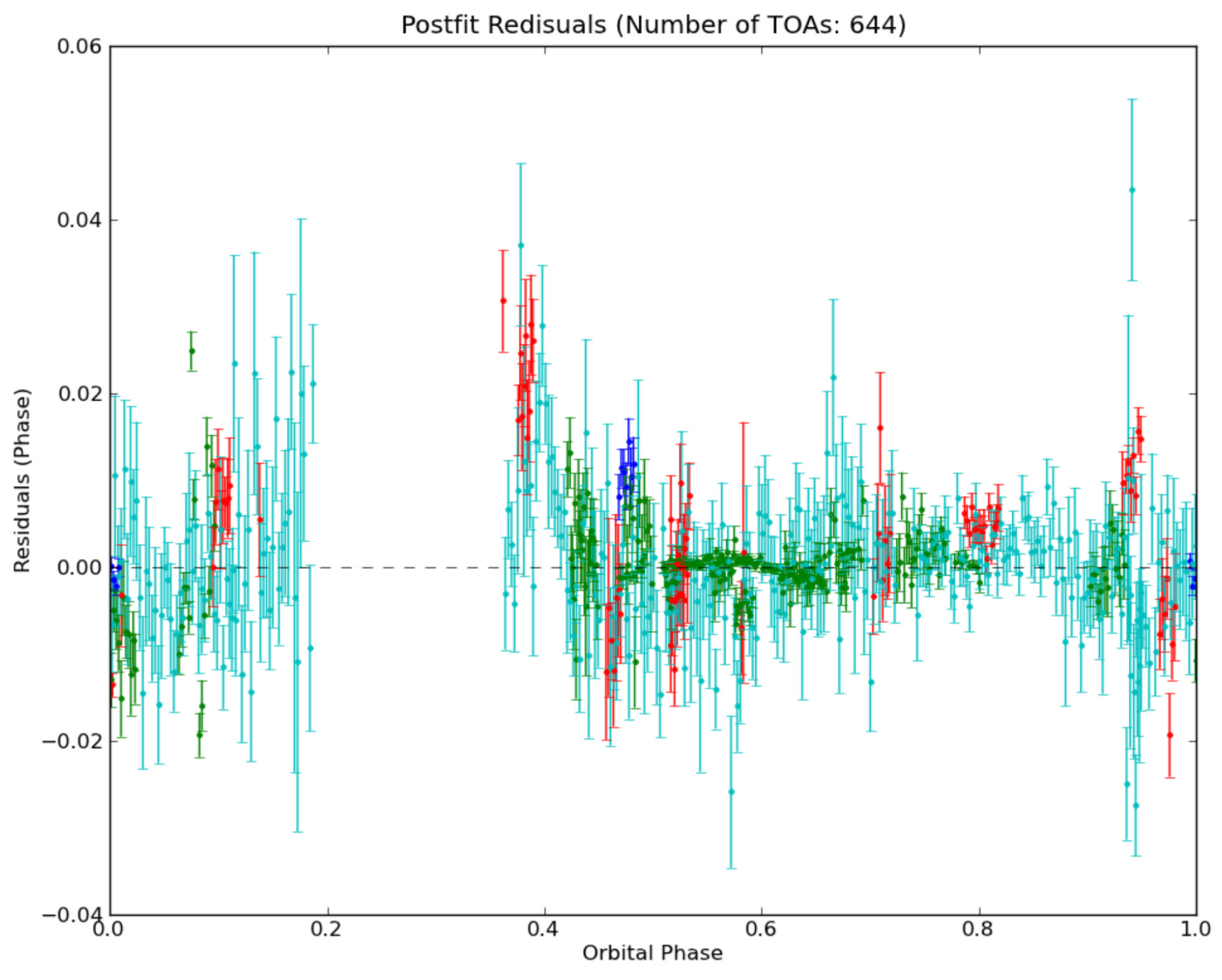


NuStar Hardness Ratio

GBT Radio Polarization



Radio Eclipse



PSR J1628-3205

- $P = 3.2$ ms
- $P_B = 5.0$ hr
- $B_{surf} = 1.8 \times 10^8$ G
- DM = 42.1 pc cm^{-3}
- $\dot{E} = 1.2 \times 10^{34}$ erg s^{-1}
- D ~ 1.3 kpc
- $M_C \sim 0.2\ M_{sun}$

Magnetic Shock Radius

We calculate a shock radius under the assumption that a magnetic wind is terminated by the magnetic field of the companion when the magnetic field in the toroidal equatorial sheet is equal in magnitude to the companion field. We assume that the pulsar field drops off as r^{-3} out to the light cylinder, and then drops off linearly out to the shock, while the companion field drops off as r^{-3} out to the shock. We define r_s as the distance from the pulsar to the shock, D as the orbital separation, R_C as the companion radius, $R_{lc} = cP/2\pi$ as the light cylinder radius and P as the pulseperiod, $B_{lc} = B_p(R_p/R_{lc})^3$ as the magnetic field at the light cylinder with B_p being the pulsar magnetic field at the pulsar surface and R_p being the radius of the pulsar, and B_c as the dipolar component of the companion’s magnetic field at the surface of radius R_c. Then, if we define $x = r_s/D$ and we define:

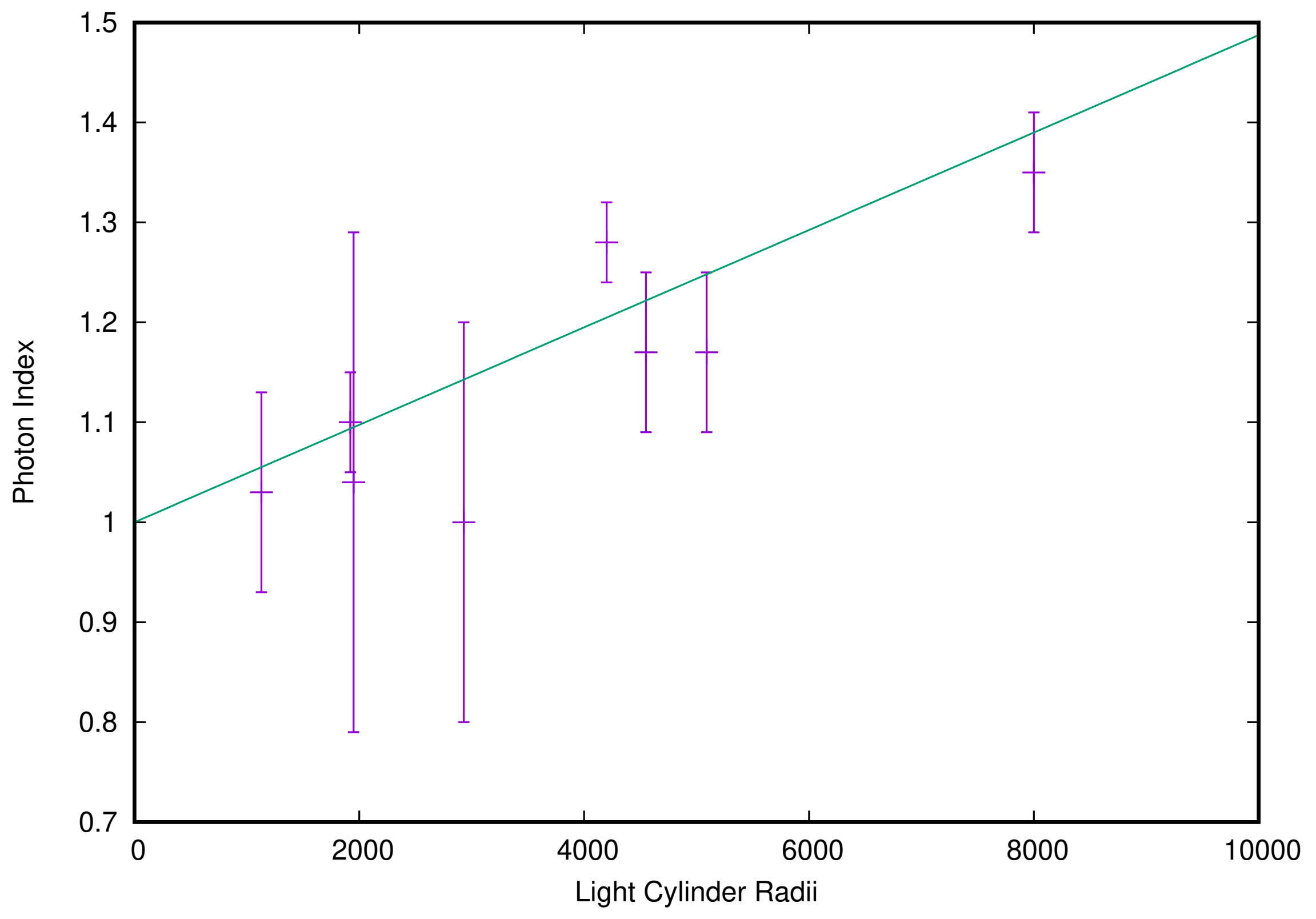
$$A = (B_{lc}/B_c)(R_{lc}/D)[(D - r_s)/R_c]^3$$

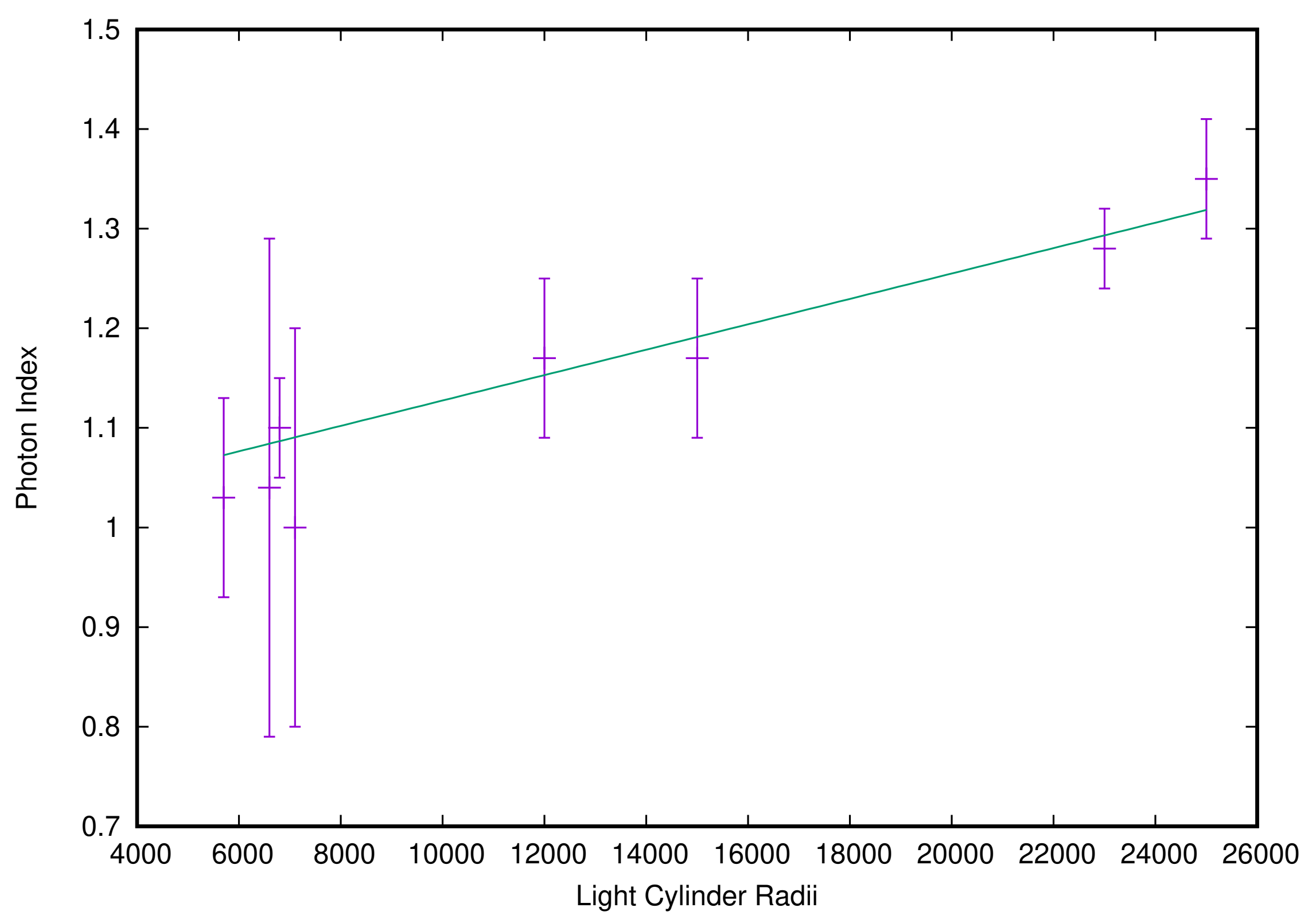
then we obtain a simple equation for the distance from the pulsar to the shock in units of the fraction of the orbital separation of the pulsar and the companion:

$$x = A(1 - x)^3$$

We calculate this value assuming $B_c = 1$ kG, $R_p = 10$ km, and $B_p = 3.2 \times 10^{19}\ (P\dot{P})^{1/2}$ G. There are numerous caveats to all of these values, with the biggest uncertainty in the companion dipolar magnetic field B_c, which is unknown, but likely around a few kG (Kochukhov et al. 2017).

NuStar Redbacks Shock Photon Index





Radius of Pulsar Wind Termination Shock if Against

Companion Magnetic Field

(Assumed 1 kG Surface Field)

Companion Surface