Physical Models for Accreting Pulsars at High Luminosity

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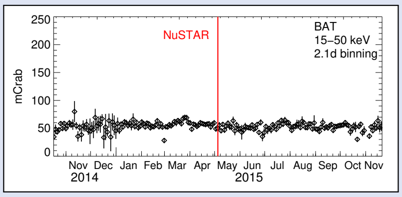
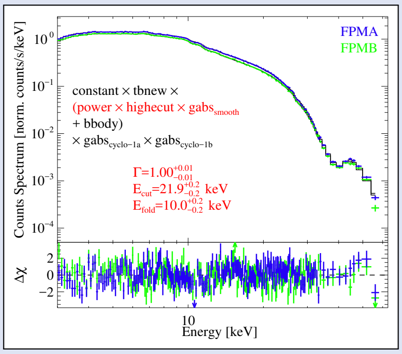
231st AAS Meeting – National Harbor, MD, USA, January 8–12, 2018

Abstract

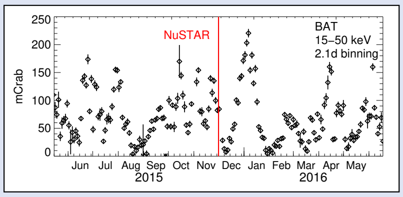
A new window for better understanding the accretion onto strongly magnetized neutron stars in X-ray binaries is opening. In these systems the accreted material follows the magnetic field lines as it approaches the neutron star, forming accretion columns above the magnetic poles. The plasma falls toward the neutron star surface at near-relativistic speeds, losing energy by emitting X-rays. The X-ray spectral continua are commonly described using phenomenological models, i.e., power laws with different types of curved cut-offs at higher energies. Here we consider high luminosity pulsars. In these systems the mass transfer rate is high enough that the accreting plasma is thought to be decelerated in a radiation-dominated radiative shock in the accretion columns. While the theory of the emission from such shocks had already been developed by 2007, a model for direct comparison with X-ray continuum spectra in xspec or isis has only recently become available. Here we analyze the broadband X-ray spectra of the accreting pulsars Centaurus X-3 and 4U 1626−67 obtained with *NuSTAR*. We present results from traditional empirical modeling as well as successfully apply the radiation-dominated radiative shock model. We also fit the energy-dependent pulse profiles of 4U 1626−67 using a new relativistic light bending model.

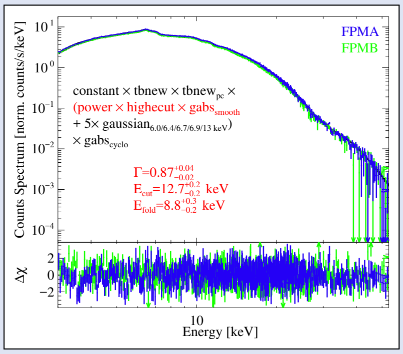
4U 1626−67





Centaurus X-3





4U 1626−67 and Centaurus X-3 are long-known, persistent, bright accreting pulsars. Both show a cyclotron line allowing us to estimate their *B*-field strength. Their recent observations with *NuSTAR* – see upper figures to the left and right for long-term flux context – are aimed at studying their broadband spectra and cyclotron lines with unprecedented sensitivity.

	4U 1626−67	Centaurus X-3
Pulse Period [s]	~7.8	~4.8
Orbital Period	42 min	2.1 d
Opt. Companion	KZ TrA	O6–8 III
Accr. Type	Disk	Wind
Cyclotron Line Energy [keV]	~37	~30
B-field [10^{12} G]	4.2	3.4
Date *NuSTAR*	2015-05-04	2015-11-30
Exposure *NuSTAR* [ks]	65	22
Distance [kpc]	9	5.7
$L_{3-50\,\mathrm{keV}}$ *NuSTAR* [10^{37} erg s^{-1}]	1.2	1.5

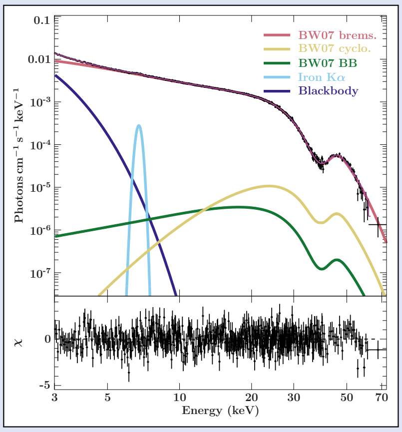
Empirical Spectral Continuum

Empirical continuum models consisting of power laws with a range of rollover parametrizations are typically used to describe the broadband spectra of these and other pulsars (Müller et al., 2013, A&A, 551, 6). Here we apply a power law (slope Γ) with an exponential cutoff (curvature E_{fold}) starting at a cutoff energy (E_{cut}) and smoothed around it (`power×highecut×gabs`).

⇐ **A good fit is obtained for 4U 1626−67** ($\chi^2_{\mathrm{red}} = 1.29$), including interstellar absorption and a previously seen blackbody and 6.7 keV iron line. More details are discussed by Iwakiri et al., 2018, ApJ, subm.. The *NuSTAR* data for the first time allow us to detect a **complex cyclotron line shape**, modeled using two components (Iwakiri+18; D'Aì et al., 2017, MNRAS, 470, 2457).

⇒ **A good fit is obtained for Centaurus X-3** ($\chi^2_{\mathrm{red}} = 1.09$), including partially and fully covering absorption, complex iron line components (6 keV, neutral, He-like, H-like), a "13 keV bump" (not always required), and the cyclotron line. Mostly known, these components are described in detail using *Suzaku* by Marcu-Cheatham et al., 2018, MNRAS, in prep.. The *NuSTAR* observation was designed to cover a similar "state" (orbital phase range).

4U 1626−67



Accretion rate	10^{17} g s^{-1}	0.760
Comptonizing temperature	keV	$4.66^{+0.11}_{-0.12}$
Column radius	m	19.1 ± 0.5
ξ-parameter		1.106 ± 0.020
δ-parameter		$4.12^{+0.26}_{-0.23}$
N_{H}	10^{22} cm^{-2}	0.1
Blackbody temperature	keV	$0.467^{+0.018}_{-0.017}$
Fe line energy	keV	6.76 ± 0.05
Cyclo. line $E_{\mathrm{cyc,1a\&1b}}$	keV	$38.8^{+0.4}_{-0.7}$, $34.1^{+1.7}_{-3.2}$
Reduced χ^2 (dof)		1.05 (506)

Physical Spectral Continuum

Here we consider accreting pulsars at high luminosity, e.g., $L_{\mathrm{X}} \gtrsim L_{\mathrm{crit}} \sim 10^{37}$ erg s^{-1} (Becker et al., 2012, A&A, 455, 123). They accrete through accretion columns above the magnetic poles within which the plasma is primarily decelerated in **radiation-dominated radiative shocks**. An analytical solution for the radiative transport equation has been provided by Becker & Wolff, 2007, ApJ, 654, 435 (BW07), where the column integrated flux is the sum of three Comptonized seed photon components:

$$F(E) = (4\pi D)^{-1}\,[\Phi^{\mathrm{brems.}}(E) + \Phi^{\mathrm{cyclo.}}(E) + \Phi^{\mathrm{BB}}(E)]$$

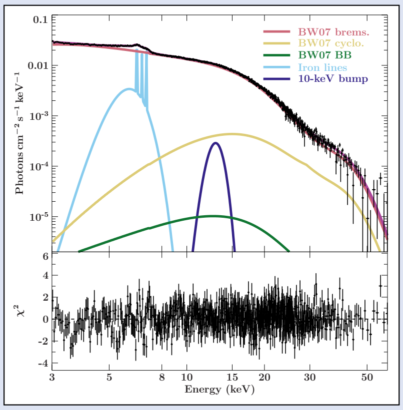
Two implementations for fitting of the analytical solution have been created and successfully applied (Ferrigno et al., 2009, A&AB, 498, 825; Wolff et al., 2016, ApJ, 831, 194 [W16, used here]), as well as a numerical one (Farinelli et al., 2016, A&A, 591, 29).

W16 provide the accretion rate (here determined based on the empirical flux measurement), Comptonizing plasma temperature, accretion column radius, as well as ξ and δ. The latter two parameters describe the ratio of the accretion- and esacpe time below the shock and the ratio of the importance of bulk and thermal Comptonization: $\xi \approx 4.2 t_{\mathrm{shock}}/t_{\mathrm{escape}}$ and $\delta = 4 y_{\mathrm{bulk}}/y_{\mathrm{thermal}}$.

Applying this continuum model to fit the *NuSTAR* spectra of 4U 1626−67 and Centaurus X-3, we obtain:

- ⋆ **good fits with χ^2_{red} values ≲ those of the empirical fits,**
- ⋆ **physically reasonable parameter values – see tables ⇐ & ⇒,**
- ⋆ fits that require the same additional components as the empirical fits (e.g., the blackbody in 4U 1626−67 or the 13 keV bump in Centaurus X-3),
- ⋆ and parameters for 4U 1626−67 similar to the more complex model by D'Aì et al., 2017, MNRAS, 470, 2457, and for Centaurus X-3 to the *Suzaku* fit of Marcu-Cheatham et al., 2018, MNRAS, in prep. (taking into account the lower luminosity here).

Centaurus X-3

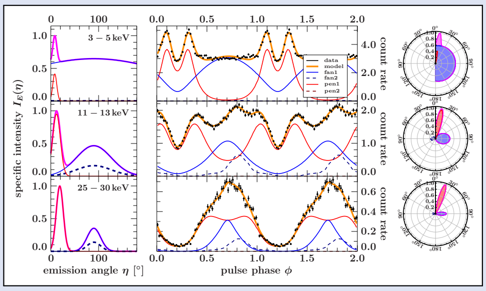


Accretion rate	10^{17} g s^{-1}	0.910
Comptonizing temperature	keV	$4.16^{+0.27}_{-0.20}$
Column radius	m	$16.4^{+2.9}_{-1.8}$
ξ-parameter		$1.05^{+0.13}_{-0.07}$
δ-parameter		$2.9^{+0.5}_{-0.6}$
N_{H}	10^{22} cm^{-2}	1.65
$N_{\mathrm{H,pc}}$, f_{pc}	10^{22} cm^{-2}, –	4.86, 0.263
"Bump" energy	keV	$12.96^{+0.25}_{-0.22}$
Compton shoulder (?)	keV	$5.98^{+0.05}_{-0.06}$
Fe line energies	(3×) keV	6.40, 6.70, 6.97
Cyclo. line E_{cyc}	keV	$29.1^{+0.5}_{-0.4}$
Reduced χ^2 (dof)		0.98 (1373)

Physical Pulse Profile – 4U 1626−67

The middle panels in the figure to the right show the pulse profiles of the *NuSTAR* observation of 4U 1626−67 as well as a fitted model composed of the emission of two accretion columns that each emit a "fan" and a "pencil" beam component (Iwakiri et al., 2018, ApJ, submitted). Each component is described by a Gaussian emission pattern G, leading to an emissivity at a given energy of $I_E(\eta) = G_{1,\mathrm{fan}} + G_{1,\mathrm{pencil}} + G_{2,\mathrm{fan}} + G_{2,\mathrm{pencil}}$, where η is the emission angle wrt the *B*-field (left and right panels ⇒).

A relativistic light bending code is used to translate these emission patterns into the observed pulse profiles (Falkner et al., 2018, A&A, to be submitted). **This setup allows for a good description of the characteristic energy-dependent pulse profiles of 4U 1626−67, from two narrow peaks at low- to a broad single peak at high energies.**



Acknowledgments

We acknowledge support by *NuSTAR* Cycle 1 GO NASA grants NNX15AV16G and NNX15AV17G (DMC, KP), as well as 2012 NASA ADAP grant NNH13AV18I / 2014 NRL BAA grant N00173-14-1-G007 (MTW, DMC, KP). We also thank the CRESST GSFC Summer Internship Program, the CRESST *Suzaku* project, and *Suzaku* Cycle 3 GO NASA grant NNX09AO90G (AMG, DMC, KP).