A relativistic light bending code is used to translate these emission files of 4U 1626–67 into a "fan" and a "pencil" beam component (Iwakiri et al., 2013). These components are described in detail using empirical models. Here we apply the broad 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 relativistic shock model. We also fit the energy-dependent pulse profiles of 4U 1626–67 using a new relativistic light bending model.

### Centaurus X-3

#### 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 consisting 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 $E_{\gamma}(\ell, \phi) = G_{\text{fan}} + G_{\text{pencil}}$, where $E_{\gamma}$ is the energy and $\ell$ and $\phi$ are the direction variables.

A relativistic light bending code is used to translate these emission patterns into the observed pulse profiles (Falkner et al., 2018, A&A, in preparation). 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.

#### Physical Spectral Continuum

Here we consider accreting pulsars at high luminosity, e.g., $L_{\text{acc}} > 10^{38}$ 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 deionized in radiation-dominated relativistic 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 $F(E) = (4\pi E)^{-1} \delta_0 (E) \Phi_\text{cyclo}(E)$.


We fit the accretion rate (here determined based on the empirical flux measurement), Comptonizing plasma temperature, accretion column radius, as well as $\gamma$ and $\beta$. The last two parameters describe the ratio of the accretion- and escape time below the shock and the ratio of the importance of bulk and thermal Comptonization: $f = \gamma^2 - 2 \gamma + \beta \sin^2 \phi$.

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

- good fits with $\chi^2$ values, those of the empirical fits, physically reasonable parameter values — see tables and fits — that fit the same additional components as the empirical fits (e.g., the blackbody in 4U 1626-67 and the 13 keV bump in Centaurus X-3),

#### Empirical Spectral Continuum

Empirical continuum models consisting of power laws with a range of additional phenomenological models 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 $\Gamma$) with an exponential cutoff (curvature $E_{\text{cut}}$) starting at a cutoff energy $(E_{\text{cut}} + \phi)$ and smoothed around it (power $\phi$) at $\text{cut} (\phi, \text{gabs})$.

$\phi = \gamma \left( E_{\text{cut}} + \phi \right)$, including interstellar absorption and a previously seen blackbody and 6.7 keV iron line. More details are discussed by Iwakiri et al., 2018, ApJ, submitted. The NuSTAR data for the first time allow us to detect a complex cyclotron line shape modeled using two components (Iwakiri et al., 2018, D’Ai et al., 2017, MNRAS, 470, 2457).

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

Acknowledgments

We acknowledge support by NuSTAR Cycle 1 GO NASA grants NNX15AV16G and NNX15AV17G (DMC, KP), as well as 2012 NASA ADAP grant NNX12AB13I / 2014 NBL BAA grant NNX14AG81G (DMC, KP). We also thank the CRESST GAC Summer Internship Program, the CRESST Suzaku project, and Suzaku Cycle 3 GO NASA grant NN09AD90G (AMG, DMC, KP).