Physical Models for Accreting Pulsars at High Luminosity

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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 forms the magnetic field lines as it approaches the neutron star, forming accretion columns above the magnetic poles. The plasma falls towards 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 shock in the accretion column, while the synchrotron emission from such shocks had already been developed by 2007. A model for direct comparison with X-ray continuum spectra in xpepe or xis 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 shock model. We also fit the energy dependent pulse profiles of 4U 1626–67 using a new relativistic light bending model.

Acknowledgments

We acknowledge support by NuSTAR Cycle 1 GO NASA grants NNX15AV16G and NNX15AV17G (DMC, KP), as well as 2012 NASA ADAP grant NNH12AA14I / 2014 NRL BAA grant N00173-14-1-0007 (MTW, DMC, KP). We also thank the CRESST GCSC Summer Internship Program, the CRESST Suzaku project, and Suzaku Cycle 3 GO NASA grant NNX09AD90G (AMG, DMC, KP).

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Empirical Spectral Continuum

Empirical continuum models consisting of power laws with a range of different parameters 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 $\alpha$) with an exponential cutoff (curvature $\xi_{\text{diff}}$) starting at a cutoff energy ($E_{\gamma\text{cut}}$) and smeared around it (power law + highecut + gabs).

$\chi^2 = \text{A good fit is obtained for } 4U 1626–67$ ($\chi^2 = 1.29$), 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 componennts (Iwakiri-18, D’Alai et al., 2017, MNRAS, 470, 2457).

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

Physical Spectral Continuum

Here we consider accreting pulsars at high luminosity, e.g., $L_{\text{1.4keV}} \approx 10^{37}$ erg/s ($\approx$ 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 $\phi_{\text{em}}(E) \approx E \cdot \pi \cdot \xi_{\text{diff}} \cdot \left[\frac{E_{\gamma\text{cut}}}{E_{\gamma\text{cut}}}\right]^\alpha$ with

$F(E) = (4\pi \gamma_{1/2} \Delta \chi)^{-1} + \frac{\phi_{\text{em}}(E)}{E}$


We provide the accretion rate (here based on the empirical flux measurement), Comptonizing plasma temperature, accretion column radius, as well as $\alpha$ and $\xi_{\text{diff}}$. The latter 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 ($\xi_{\text{Th}}$ = $\Delta z_{\text{Th}} / \Delta z_{\text{bulk}}$). Applying this continuum model to fit the NuSTAR spectra of 4U 1626–67 and Centaurus X-3, we obtain:

- good fits with $\xi_{\text{Th}}$ values that are 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 13keV bump in Centaurus X-3),