

State-Dependent X-ray Variability in Cygnus X-1: A 12-Year NuSTAR Timing Study of Accretion Flow Geometry

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ABSTRACT

We present a comprehensive timing analysis of the black hole X-ray binary Cygnus X-1 using 26 NuSTAR observations spanning 2012-2024, providing the most detailed characterization to date of its accretion flow variability across spectral states. Our analysis reveals fundamental insights into the physics governing state transitions in stellar-mass black holes. We discover distinct bimodal flux distributions in the 8-79 keV band with well-separated peaks, contrasting with overlapping distributions in the 3-8 keV band. This energy-dependent bimodality establishes hard X-rays as the optimal diagnostic for state classification, directly tracing the geometric transformation between corona-dominated and disk-dominated configurations. Power spectral analysis uncovers state-dependent characteristic frequencies shifting from 0.050 Hz (hard) to 0.074 Hz (intermediate), with featureless red noise in soft states. These frequencies correspond to disk truncation radii evolving from $\sim 5.5 R_g$ to $\sim 2 R_g$, providing direct observational evidence for the inward progression of the accretion disk during state transitions. Frequency-dependent time lags evolve systematically from ~ 50 ms hard lags at 0.1 Hz in hard states to near-zero in soft states, quantifying the collapse of the Comptonizing corona. Linear rms-flux relations persist across all states with parameters that precisely track the relative contributions of thermal versus non-thermal emission components. Most remarkably, we identify a failed state transition (observation 30302019006) exhibiting anticorrelated band behavior, suppressed variability ($F_{var} < 1.38\%$), and apparent sub-ISCO truncation. This discovery challenges standard transition models and suggests new pathways for accretion flow evolution in wind-fed systems.

Keywords: X-Ray Binaries (1811) — High mass x-ray binary stars (733) — High Energy astrophysics (739) — Black hole physics (159) — Timing variation methods (1703)

1. INTRODUCTION

Microquasars are X-ray binary (XRB) systems consisting of a compact object, such as a stellar-mass black

hole or a neutron star, that is accreting matter from a stellar companion. A defining characteristic of these systems is their ability to launch collimated, relativistic jets of plasma (I. F. Mirabel & L. F. Rodríguez 1999). The discovery and subsequent study of microquasars have provided profound new insights into the physics

of accretion and ejection in the vicinity of compact objects, establishing them as scaled-down analogues of active galactic nuclei (AGNs) and quasars (I. F. Mirabel & L. F. Rodríguez 1998). These systems exhibit physical processes analogous to those in quasars, but on a significantly smaller scale. S. Chaty (2005). This analogy is founded on the common architecture of a central accreting object, an accretion disk, and bipolar jets, with physical processes scaling in proportion to the mass of the central object. Given that the timescales of variability in microquasars are millions of times shorter than in their supermassive counterparts, they serve as unique laboratories for observing the dynamics of disk-jet coupling in real time.

The first object recognized to possess relativistic jets was SS 433, whose jets, moving at a velocity of $0.26c$, were considered a galactic curiosity for many years (B. Margon 1984). The formal establishment of the microquasar class came with the discovery of large-scale, symmetric radio jets from the Galactic Center source 1E 1740.7-2942, which bore a striking morphological resemblance to the jets of extragalactic radio sources (I. F. Mirabel et al. 1992). This paradigm was unequivocally confirmed by the observation of apparent superluminal motion in the radio jets of GRS 1915+105 (I. F. Mirabel & L. F. Rodríguez (1994) and shortly thereafter in GRO J1655-40 (R. M. Hjellming & M. P. Rupen 1995; D. L. Jones et al. 1996). This phenomenon, a relativistic effect where plasma clouds ejected at near-light speed and at a small angle to the line of sight appear to travel faster than light, solidified the physical connection to quasars.

For Black Hole X-Ray Binaries (BHXBs), observational campaigns have revealed a strong coupling between the state of the accretion flow, diagnosed by its X-ray spectral and timing properties (see R. A. Remillard & J. E. McClintock (2006) for a review), and the nature of the jet. In the low/hard X-ray state, BHXBs typically exhibit a steady, self-absorbed, compact radio jet with a characteristic flat or inverted radio spectrum (R. P. Fender 2001; S. Corbel et al. 2001). As the source transitions to the high/soft state, which is dominated by thermal emission from the accretion disk, this compact jet is quenched (R. Fender et al. (1999). The transition between these states is often accompanied by major, discrete ejection events that produce transient jets observed in sources like GRS 1915+105 (R. P. Fender et al. 2004).

2. CYGNUS X-1: THE ARCHETYPAL BLACK HOLE MICROQUASAR

Cygnus X-1 is the prototypical high-mass X-ray binary (HMXB) and was the first source for which the

accretor was dynamically confirmed to be a black hole (B. L. Webster & P. Murdin 1972; C. T. Bolton 1972). The system consists of a black hole accreting from the focused stellar wind of its O9.7Iab supergiant companion, HDE 226868. Recent measurements place the system at a distance of 2.22 ± 0.18 kpc, and calculate a black hole mass of $21.2 \pm 2.2 M_{\odot}$ (J. C. A. Miller-Jones et al. 2021). Extensive observational campaigns have established that the black hole is rapidly rotating, but the precise value of the spin parameter is still a matter of debate. Various methods, including X-ray reflection spectroscopy and continuum-fitting, have been employed to constrain this parameter. For instance, early measurements using X-ray reflection spectra found the dimensionless black hole spin to be approximately $0.97^{+0.014}_{-0.02}$ (A. C. Fabian et al. 2012), consistent with continuum-fitting results that indicated an extremely high spin of $a^* > 0.983$ (L. Gou et al. 2014). More recently, updated analyses using the continuum-fitting method and refined system parameters have placed the spin at an even higher value of $a^* > 0.9985$ (3σ) (X. Zhao et al. 2021), while other studies combining continuum and reflection methods have reported values such as $a^* = 0.87^{+0.04}_{-0.03}$ (with a free disk inclination) or $a^* = 0.90^{+0.01}_{-0.01}$ (fixing inclination to optical measurements) (A. A. Zdziarski et al. 2024). Although some models incorporating a warm Comptonization layer suggest the possibility of lower spin values, the overwhelming consensus from multiple observational approaches points towards a remarkably high black hole spin in Cygnus X-1 with a spin parameter $a_* > 0.98$ derived from both modeling of the thermal accretion disk continuum (L. Gou et al. 2014) and the relativistically broadened Fe K α reflection features, e.g., (R. Duro et al. 2016).

As a persistent source, Cygnus X-1 has served as a touchstone for defining the canonical spectral states of accreting black holes, primarily the hard and soft states (E. Churazov et al. 2001). Unlike transient systems, however, it never enters a fully disk-thermal-dominant state; its soft state is more accurately described as a steep power-law state (R. A. Remillard & J. E. McClintock 2006), and the source remains on the lower, hard-state branch of the hardness-intensity diagram (J. F. Steiner et al. 2024). In the hard state, the spectrum is dominated by a power-law component produced by inverse Compton scattering in a hot corona, which exhibits a high-energy cutoff around 100 keV (F. Cangemi et al. 2019). This state is accompanied by a persistent, compact relativistic jet (R. P. Fender et al. 2006) and a non-thermal, polarized tail extending to MeV energies, likely synchrotron emission from the jet base (Zanin, R. et al. 2016).

The source’s timing behavior is also state-dependent. The hard state exhibits strong, broadband variability whose power spectrum is well-modeled by a superposition of Lorentzian components (K. Pottschmidt et al. 2000). In the soft state, the variability drops to ~ 10 -20% root mean square (rms) and is characterized by red noise (W. Cui et al. 1996). The linear relationship between rms variability and flux observed across timescales suggests that accretion rate fluctuations propagate through the flow (P. Uttley & I. M. McHardy 2001).

X-ray observations have been instrumental in characterizing the physical properties of Cygnus X-1’s accretion flow and corona. Various X-ray observatories, including *INTEGRAL* (Cadolle Bel, M. et al. 2006), *Suzaku* (M. L. Parker et al. 2015), and *Chandra* (M. A. Nowak et al. 2011), have provided detailed spectral and timing analyses that have shaped our understanding of this system. X-ray spectroscopy has enabled detailed modeling of reflection components originating from material near the black hole. These analyses constrain parameters such as black hole spin, inner disk radius, and coronal properties (J. Tomsick 2018; Y. Zhu et al. 2024).

The Nuclear Spectroscopic Telescope Array (*NuSTAR*) (F. A. Harrison et al. 2013), launched in 2012, has provided unprecedented sensitivity in the hard X-ray band (3–79 keV), offering new insights into high-energy processes occurring in Cygnus X-1. Its focusing optics deliver significantly improved spatial and spectral resolution compared to previous hard X-ray instruments.

NuSTAR observations have been used to test fundamental aspects of General Relativity by analyzing reflection features in spectra to constrain black hole spin parameters (M. L. Parker et al. 2015). For example, joint *NuSTAR* and *Suzaku* observations constrained Cygnus X-1’s spin parameter to values between 0.861 and 0.921 using advanced models like *kerrC*, which account for complex coronal geometries. Additionally, *NuSTAR* analyses favor extended wedge-shaped coronae over compact lamp-post configurations for explaining observed spectra. These findings challenge simplified models while advancing our understanding of accretion flows near black holes (H. Krawczynski & B. Beheshtipour 2022).

3. *NUSTAR* OBSERVATIONS AND DATA REDUCTION

We processed all *NuSTAR* observations of Cygnus X-1 with issue flag 0 using the *NuSTAR* Data Analysis Software (*NuSTARDAS*) provided within the HEASoft (Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014) environment, along with

the corresponding Calibration Database (CALDB) June 30, 2025 update. A log of these data is given in Table 1. For each Observation ID (OBSID), the raw Level 1 data were reprocessed using the *nupipeline* tool. This standard pipeline task performs instrument calibration, applies coordinate transformations, and generates cleaned, calibrated Level 2 event files for both Focal Plane Modules, FPMA and FPMB.

During pipeline execution, standard screening criteria were applied to the event data to filter for good time intervals (GTIs). We selected science-grade events and filtered out periods of high particle background identified by the CsI anti-coincidence shield. This procedure ensures the use of high-quality data and maximizes the signal-to-noise ratio.

Following the initial processing, we extracted scientific products from the cleaned Level 2 event files using the *nuproducts* tool. For both FPMA and FPMB in each observation, source products were extracted from a circular region with a radius of 120'' centered on the nominal J2000 coordinates of Cygnus X-1. The background was estimated from a nearby, source-free circular region of the same size located on the same detector chip. A critical step for our timing analysis was the application of a barycentric correction to adjust photon arrival times to the solar system barycenter; this was performed by setting the *barycorr=yes* parameter in *nuproducts*. This process generated the necessary source and background spectra, light curves, ancillary response files (ARFs), and redistribution matrix files (RMFs).

The final, background-subtracted light curves for each observation were then produced using the *lcmath* FTOOL. For a given OBSID, the source light curves from FPMA and FPMB were summed to create a combined source light curve. The corresponding background light curves were similarly summed. The final light curve was then created by subtracting the combined, area-scaled background from the combined source, resulting in a single, high signal-to-noise light curve for each observation, ready for timing analysis.

To finalize the light curves for analysis, we first extracted them at multiple time resolutions (0.1 s, 1 s, 10 s, 100 s, and 300 s) to assess the balance between temporal detail and statistical quality. For the primary timing analysis, we selected the 0.1 s resolution. This choice maximizes sensitivity to the rapid, aperiodic X-ray variability that is a key characteristic of accreting black hole systems like Cygnus X-1. For all analyses except two, we utilize the 0.1 s observations. To mitigate the influence of outliers, we filtered the selected light curves by removing data points with count rates below the 1st

percentile or above the 99th percentile. This conservative clipping procedure is designed to remove the most extreme statistical fluctuations in the tails of the count rate distribution, which could otherwise disproportionately affect variance-based analyses. We found that, on average, 0.01% of points were removed per observation.

4. ANALYSIS AND RESULTS

4.1. *Timing Analysis*

4.1.1. *Long-Term Spectral Evolution*

We tracked the long-term X-ray evolution of Cygnus X-1 across the entire *NuSTAR* observational campaign. Figure 1 presents the total intensity (3-79 keV) light curve, constructed from 100s time bins, with each point color-coded by its corresponding hardness ratio (HR). The x-axis represents the sequence of individual *NuSTAR* observations, stitched together to visualize the source’s behavior over time.

The source exhibits profound variability in both its flux and spectral shape, with multiple transitions between the canonical hard and soft spectral states clearly visible. The hard state is prominent throughout many observations (e.g., Obs. 30002150002), characterized by a relatively low intensity of approximately 400-800 counts/s and a high HR, indicated by yellow and orange points. Conversely, the soft state manifests as periods of high intensity (>1000 counts/s) and a low HR, indicated by purple and blue points. A particularly dramatic flare event is captured in Obs. 30302019010 and Obs. 30302019012, where the source intensity exceeds 2500 counts/s while the spectrum becomes exceptionally soft. This comprehensive view of Cygnus X-1’s rich and complex behavior demonstrates the clear spectral state transitions that motivate our detailed analysis of the optimal energy bands for characterizing these states.

4.1.2. *Orbital Phase Coverage*

Given Cygnus X-1’s 5.6-day orbital period and the temporal distribution of our observations, we examined the orbital phase coverage achieved by our *NuSTAR* campaign. Using the orbital ephemeris of (C. Brocksopp et al. 1999) with $P = 5.599829$ days and $T_0 = \text{MJD } 41874.207$, we computed the orbital phase for each observation segment.

Figure 2 displays the orbital phase sampling across the three spectral states identified from our hardness ratio analysis. The soft state observations (top panel) provide nearly complete orbital coverage with enhanced sampling near phases 0.1 and 1.1, fortuitously capturing the system during multiple orbital cycles. The intermediate state (middle panel) achieves approximately 50% phase coverage, with observations concentrated between

phases 0.0-0.4 and a secondary cluster near phase 1.1. The hard state (bottom panel) offers the most comprehensive coverage, with observations distributed across nearly the entire orbital cycle, enabling robust characterization of any orbital-dependent phenomena.

This differential phase coverage must be considered when interpreting state-dependent orbital modulation patterns. While the incomplete intermediate state coverage may affect the measured modulation amplitudes, the excellent hard and soft state sampling ensures that the observed differences in orbital variability between these states represent genuine physical effects rather than sampling biases.

4.1.3. *Energy Band Selection*

The distinct spectral states evident in Figure 1 require careful selection of energy bands for constructing a robust hardness ratio. Given that specific energy ranges are highly instrument-dependent and must be tailored to both source characteristics and detector response, we performed a data-driven analysis to define optimal bands for tracking Cygnus X-1’s state transitions. We examined count rate distributions at key energy boundaries, with Figure 3 showing histograms for three representative bands: 3-8 keV, 8-79 keV, and 20-79 keV, each normalized to their maximum values for direct comparison.

The distributions reveal striking energy-dependent evolution. The 3-8 keV band (panel a) shows a broad, unimodal distribution skewed toward lower count rates. In contrast, the 8-79 keV band (panel b) exhibits clear bimodality with well-separated peaks at approximately 200 and 400 counts/s. This bimodality persists in harder bands (panel c) despite lower statistics. This energy-dependent structure has clear physical origins. Below 8 keV, thermal disk emission dominates, varying continuously as disk temperature evolves from 0.2 keV (truncated hard state) to 0.4-0.5 keV (extended soft state). Above 8 keV, Comptonized emission dominates: either from an extended, geometrically thick corona (hard state) producing substantial hard X-rays, or from a largely suppressed corona (soft state) with minimal hard emission. The bistable nature of these configurations—driven by thermal and radiative instabilities—creates the observed bimodal distribution in hard X-rays while preserving continuous variation in the thermal component. The emergence of clear bimodality above 8 keV—coincidentally near *NuSTAR*’s peak effective area—motivated our band definitions: 3-8 keV (soft) and 8-79 keV (hard), naturally separating thermal from Comptonized emission. To quantify these distributions, we performed model comparison using Nor-

Table 1. Log of NuSTAR observations used in this work

Start Date (YYYY-MM-DD)	End Date (YYYY-MM-DD)	ObsID	Exposure (s)	Start Time (UTC) (HH:MM:SS)
2012-11-01	2012-11-01	10014001001	4184	17:16:08
2017-11-04	2017-11-04	30201902001	9400	00:16:13
2016-05-29	2016-05-30	30002015004	50602	21:26:12
2022-09-20	2022-09-20	90801302002	13178	12:05:08
2024-07-12	2024-07-12	91002023004	13718	14:56:07
2014-05-20	2014-05-20	30001011007	34372	05:51:04
2016-05-27	2016-05-28	30002015002	50077	22:41:05
2015-05-27	2015-05-27	30101022002	19861	17:06:09
2022-05-21	2022-05-21	90801302001	13781	10:26:07
2018-05-27	2018-05-27	30203019010	8214	08:31:12
2022-05-20	2022-05-20	30702017006	12367	14:06:12
2023-06-14	2023-06-14	80902318004	9326	00:26:12
2023-05-28	2023-05-28	80902318002	13507	05:31:08
2024-04-08	2024-04-09	80902319002	16879	18:16:08
2012-10-31	2012-10-31	30001011002	10442	08:11:11
2019-11-13	2019-11-13	80502335006	11914	10:06:06
2015-01-19	2015-01-19	30101011011	16824	00:36:09
2016-02-11	2016-02-11	90101020002	13472	10:51:10
2014-10-04	2014-10-04	30001011009	20355	17:36:08
2018-02-08	2018-02-08	30203019004	12708	02:01:06
2018-08-11	2018-08-11	30203019012	12119	03:01:09
2019-08-06	2019-08-06	80502335002	13436	09:01:09
2016-07-18	2016-07-18	30203022002	13312	15:31:06
2014-04-23	2014-04-24	30001011006	13507	22:11:08
2018-03-26	2018-03-26	30203019008	11024	17:46:11
2016-06-22	2016-06-23	30002015006	38717	22:01:13

mal, Lognormal, and bimodal variants (Gaussian Mixture Models), selecting optimal models via the Bayesian Information Criterion. Figure 4 presents the results.

While both soft and total bands are best described by overlapping bimodal lognormal models, the hard band exhibits a distinct two-component GMM with well-separated peaks. This confirms that hard X-rays preferentially occupy two distinct flux states, validating our hardness ratio as a robust state discriminator: the hard band’s clear bimodality provides state separation while the soft band’s overlapping components reflect gradual thermal evolution during transitions.

Below 8 keV: Emission is primarily from the thermal accretion disk, whose temperature and luminosity vary continuously with radial movement. During state transitions, the disk temperature evolves smoothly from ~ 0.2 keV (R. Basak et al. 2017) (in the truncated hard state) to $\sim 0.4 - 0.5$ keV (in the extended soft state,

reaching the ISCO) (D. J. Walton et al. 2016). This results in a continuum of flux values rather than discrete states, accounting for the broad, unimodal distribution.

Above 8 keV: The emission is dominated by Comptonization in the corona and/or jet base. In the hard state, a geometrically thick, optically thin corona generates substantial hard X-ray emission via inverse Compton scattering. In the soft state, this corona is largely suppressed or collapsed, reducing hard X-ray production. The intermediate state reflects brief transitions between these configurations. As the corona is either extended (hard state) or suppressed (soft state), with limited time in transitional geometries, the hard X-ray flux naturally bifurcates into two distinct levels.

The increasing separation between peaks at higher energies (see 3b and 3c) further supports this interpretation. As the energy (or temperature) of the Comptonizing electrons increases, the Comptonization efficiency

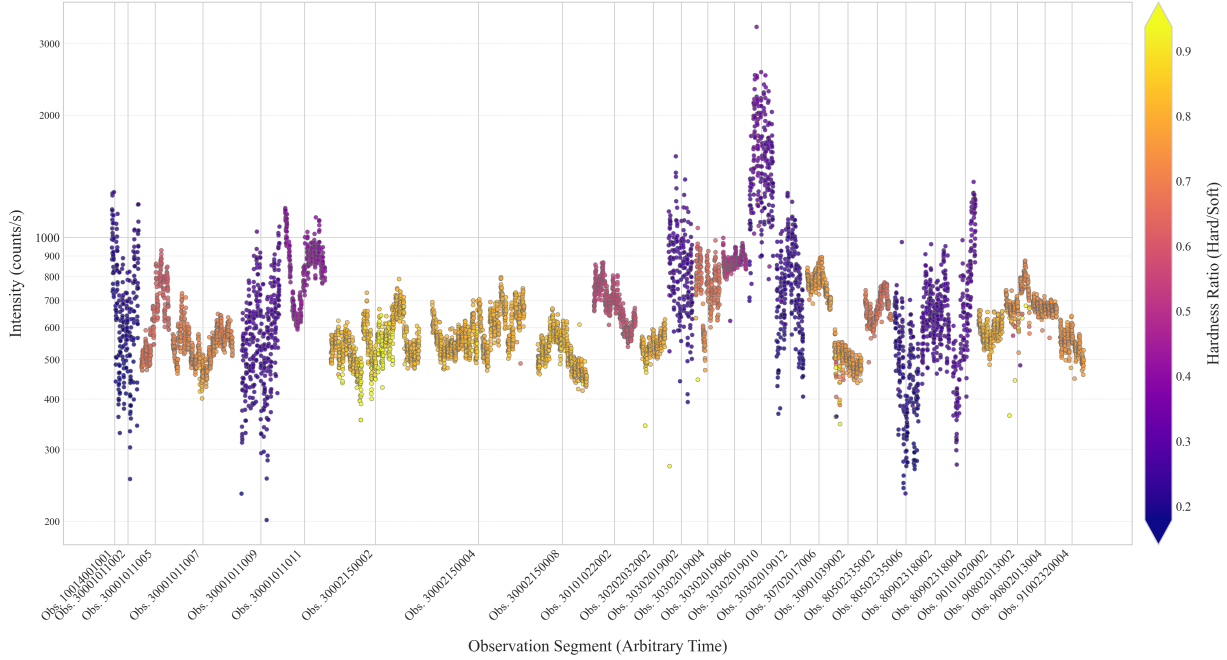


Figure 1. The long-term evolution of Cygnus X-1’s intensity and spectral hardness. Each point represents a 100s time bin, with observation segments separated for visual clarity. The y-axis shows the total intensity in the 3-79 keV band, and the color of each point corresponds to the hardness ratio (HR), defined as the 8-79 keV rate divided by the 3-8 keV rate. Yellow/orange colors indicate a harder spectrum, while purple/blue colors indicate a softer spectrum, clearly showing the source transitioning between hard and soft states.

risers, with the extended hard-state corona upscattering photons to higher energies than the collapsed soft-state corona. This bimodality reflects the bistable nature of accretion flows around black holes, driven by thermal and radiative instabilities that push the system toward either a cool, geometrically thin disk or a hot, geometrically thick flow, with rapid transitions between these configurations.

Having established the optimal energy ranges, we next sought to quantitatively characterize the statistical nature of the count rate distributions within them. We analyzed the distributions for the total (3-79 keV), soft (3-8 keV), and hard (8-79 keV) bands individually. For each distribution, we performed a model comparison to determine the best statistical description. The candidate models included a standard Normal distribution, a Log-normal distribution (which often characterizes accretion processes), and their bimodal counterparts, modeled as a Gaussian Mixture Model (GMM) with two components. The optimal model for each band was selected by finding the one with the lowest Bayesian Information Criterion (BIC), which penalizes model complexity to avoid overfitting.

The results of this analysis are presented in Figure 4. The distributions for the total band (panel a) and the soft band (panel b) are both best described by an overlapping bimodal lognormal model. Crucially,

while all bands exhibit bimodality, the nature of this bimodality differs significantly. In the soft band, the two lognormal components overlap substantially, creating a broad, nearly continuous distribution that suggests the soft emission transitions smoothly between states without clear separation. In stark contrast, the hard-band (panel c) distribution is unambiguously bimodal and is best fit by a two-component GMM with well-separated peaks. This confirms that the hard X-ray emission preferentially occupies two distinct flux states with minimal overlap. The existence of a clearly separated bimodal hard band, coupled with the overlapping bimodal soft band, validates our use of their ratio (the hardness ratio) as a robust tracer for the source’s transitions between the two fundamental accretion states clearly visible in Figure 1. The hard band’s distinct bimodality provides the discriminating power to cleanly separate the states, while the soft band’s overlapping nature reflects the more gradual thermal evolution during state transitions.

4.2. Fractional Variability and Modulation Factors

The fractional variability (F_{var}) is a crucial diagnostic for understanding the intrinsic variability in the X-ray light curves of Cygnus X-1. It is calculated as the normalized rms fluctuation in the count rates, which allows us to distinguish between true source variability

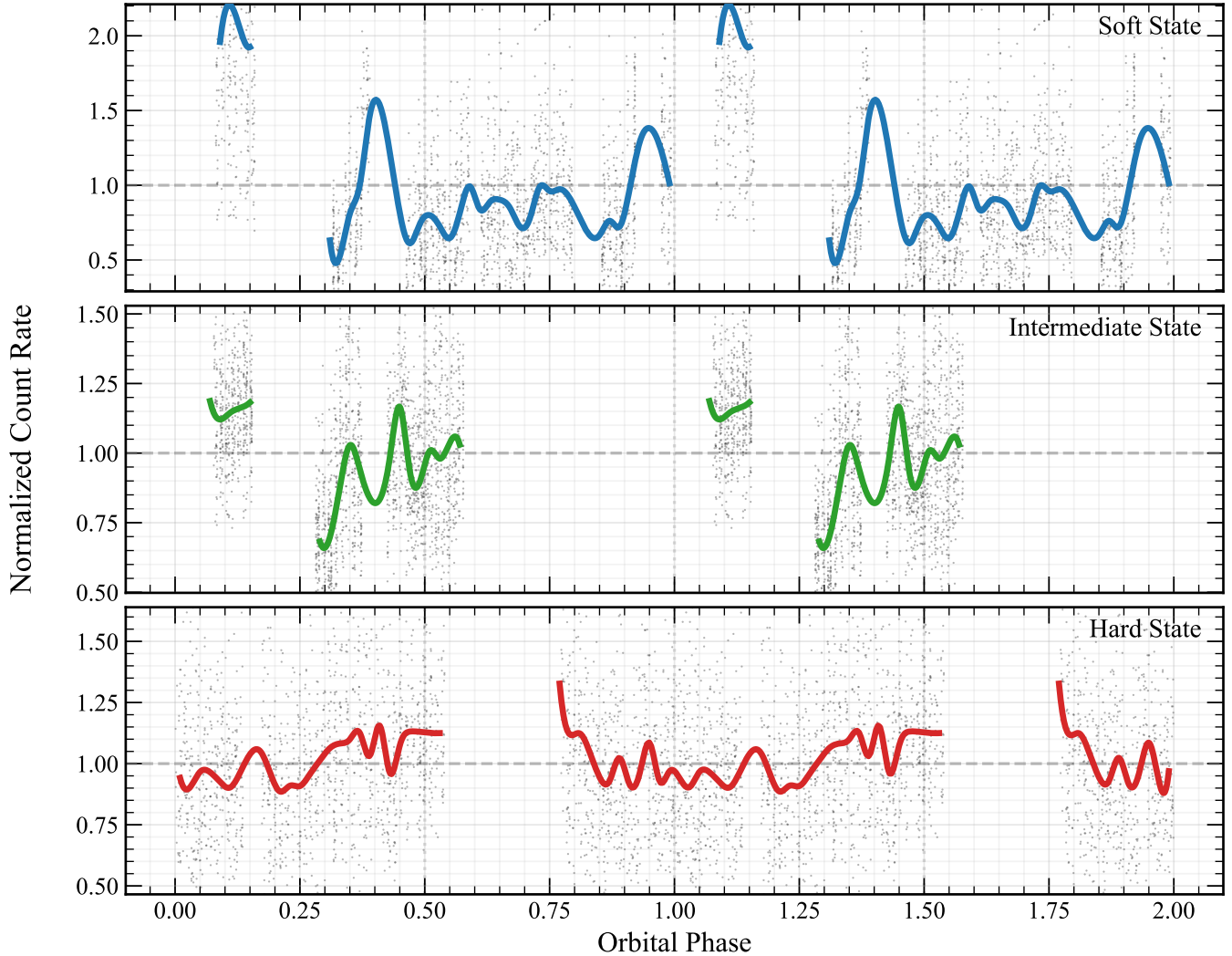


Figure 2. Orbital phase coverage of *NuSTAR* observations separated by spectral state. Gray points show individual 100s time bins phase-folded using the 5.6-day orbital period, while colored lines represent smoothed profiles normalized to the mean count rate (horizontal dashed line). Data are shown over two cycles for clarity. Soft state (top): nearly complete phase coverage. Intermediate state (middle): approximately 50% coverage concentrated at phases 0.0-0.4. Hard state (bottom): comprehensive coverage across most of the orbit.

and statistical noise. We apply the method outlined by [S. Vaughan et al. \(2003\)](#) to obtain F_{var} and its associated uncertainty.

For the majority of observations, we calculate the excess variance, and the resulting F_{var} values are reported in Table 2. However, the excess variance is negative in one case (ObsID 30302019006), which suggests that the intrinsic variability of the source is too low to be detected beyond the noise level. Therefore we instead provide a 95% confidence upper limit, derived by considering the uncertainty in the measured excess variance and applying a statistical approach to estimate the maximum possible value of F_{var} . This upper limit reflects the sensitivity of our measurements and indicates that

the variability in this observation is consistent with no intrinsic variability, within the limits of our measurement errors.

In addition to the fractional variability, we calculate the modulation factor for each observation, defined as the peak-to-trough amplitude normalized by the mean count rate. The modulation factors range from 0.385 to 0.793, providing a complementary measure of flux variations that captures the full amplitude swing rather than the rms deviation. Notably, the modulation factor shows strong correlation with F_{var} (Pearson correlation coefficient $r = 0.91$), confirming that both metrics trace the same underlying variability characteristics. The highest modulation factors (> 0.75) occur in observations with

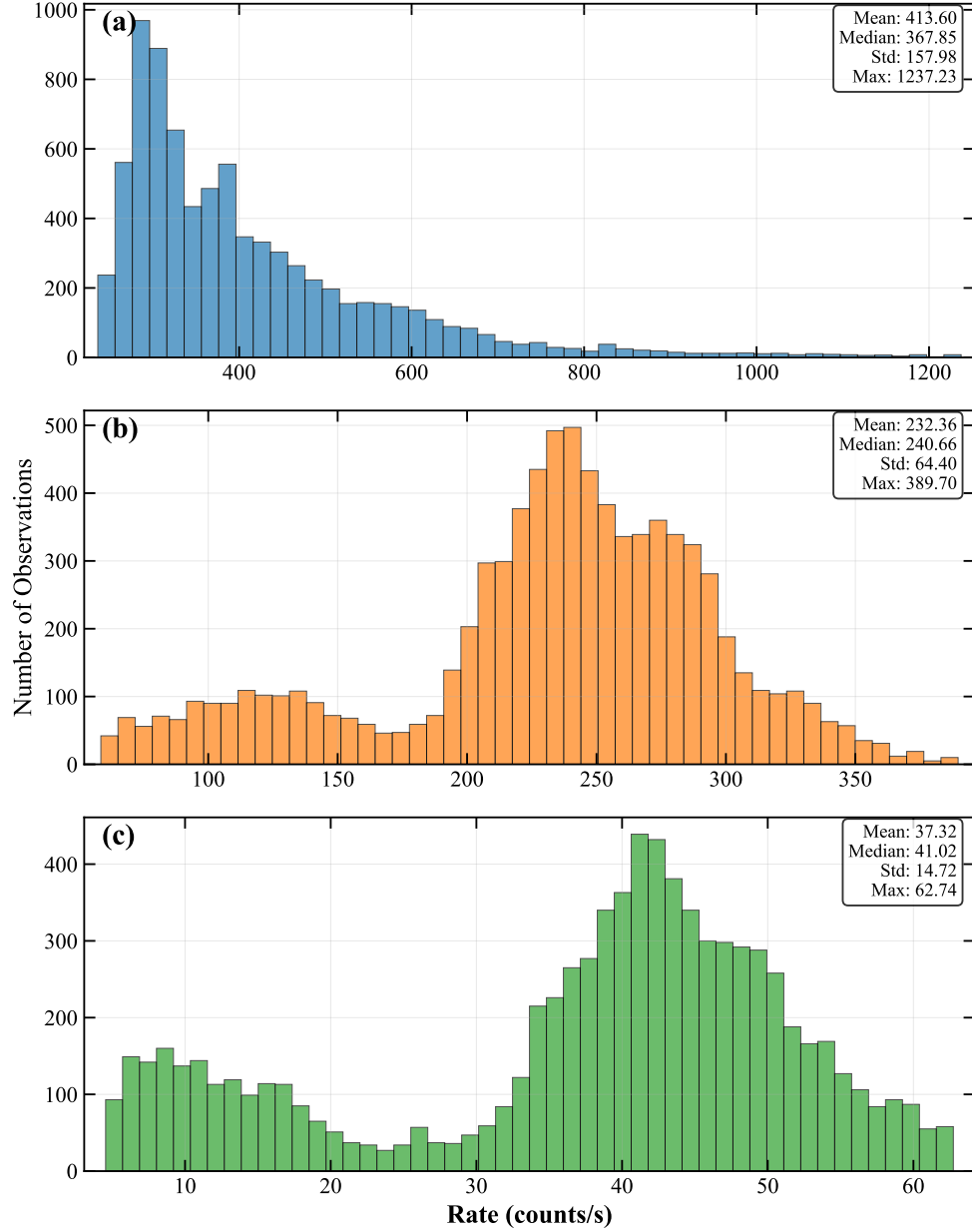


Figure 3. Count rate distributions for Cygnus X-1 across various *NuSTAR* energy bands. (a) Count rate distributions for the 3-8 keV band. (b) Count rate distributions for the 8-79 keV band. (c) Count rate distributions for the 20-79 keV band. Each panel shows a histogram of the light curve count rates for the specified energy band. A clear bimodal distribution is seen in energy bands starting at 8 keV and the bimodality remains constant as the lower end of the energy band increases, motivating our choice of the hard and soft bands.

$F_{var} > 30\%$, predominantly during soft states and state transitions. Conversely, the lowest modulation factors (< 0.52) correspond to observations with $F_{var} < 12\%$, typically in stable hard or intermediate states.

The anomalous observation 30302019006 exhibits the lowest modulation factor (0.385) alongside its non-detection in F_{var} , further reinforcing the unusual stability of this intermediate state. The consistency between these independent variability metrics strengthens

our interpretation that this observation captured a failed state transition where the usual coupling between spectral softening and enhanced variability was disrupted. The modulation factor provides additional validation that the low variability is a genuine physical characteristic rather than a statistical artifact.

The non-detection of variability in observation 30302019006, despite the source exhibiting a clear intermediate state, is striking. This state is canonically

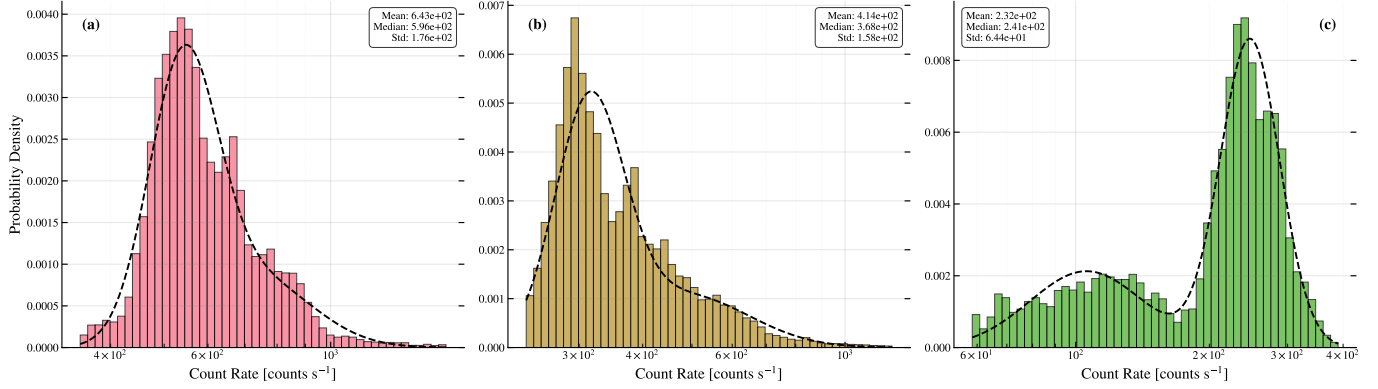


Figure 4. Distributions of the count rates for (a) the full band, (b) the soft band, and (c) the hard band. The histograms are shown on a logarithmic rate axis. The dashed line in each panel represents the best-fit model as determined by the BIC.

Table 2. Log of observations showing the start and end orbital phases and the corresponding fractional variability and modulation factors. ObsIDs marked with an asterisk (*) cross the phase 0.0 boundary. For observations where the excess variance was negative, we report the 95% confidence upper limit on the fractional variability.

OBSID	Start Phase	End Phase	Mean Flux (counts/s)	F_{var} (%)	Modulation Factor
30001011002	0.854	0.921	623.4250	37.30 ± 0.05	0.793
10014001001	0.975	0.993	865.9116	29.16 ± 0.10	0.759
30001011005	0.282	0.373	638.2865	21.79 ± 0.05	0.620
30001011007	0.910	1.110	540.8489	14.16 ± 0.04	0.567
30001011009	0.464	0.590	587.0555	34.52 ± 0.04	0.781
30001011011	0.445	0.578	839.4739	12.65 ± 0.05	0.505
30101022002	0.425	0.563	686.7302	9.84 ± 0.06	0.509
90101020002	0.807	0.886	587.0142	16.32 ± 0.06	0.576
30002150002	0.826	1.120	551.4538	21.59 ± 0.03	0.646
30002150004	0.173	0.480	589.8527	20.88 ± 0.03	0.629
30002150008	0.893	1.055	524.3749	20.92 ± 0.04	0.641
30202032002	0.058	0.137	543.3733	16.35 ± 0.06	0.590
30302019002	0.717	0.795	836.7514	29.00 ± 0.05	0.716
30302019004	0.879	0.958	752.2041	16.57 ± 0.05	0.564
30302019006	0.078	0.154	872.8378	<1.38%	0.385
30302019010	0.081	0.160	1568.9739	35.69 ± 0.04	0.757
30302019012	0.613	0.702	766.3174	32.18 ± 0.05	0.746
80502335002	0.945	1.031	674.9547	11.11 ± 0.07	0.519
80502335006	0.632	0.711	479.6962	29.12 ± 0.06	0.736
30702017006	0.773	0.852	770.8656	13.16 ± 0.06	0.526
90802013002	0.293	0.372	711.1962	11.92 ± 0.06	0.523
90802013004	0.461	0.540	672.0306	9.49 ± 0.07	0.508
80902318002	0.701	0.792	656.0478	16.41 ± 0.05	0.581
80902318004	0.316	0.390	724.7160	40.08 ± 0.05	0.787
30901039002	0.843	0.933	500.8741	17.74 ± 0.06	0.633
91002320004	0.784	0.862	547.2458	16.51 ± 0.06	0.605

associated with high levels of aperiodic variability as the accretion flow undergoes significant reconfiguration (S. Rapisarda et al. 2017). The observed quiescence suggests a decoupling of the spectral and timing evolution. One possible interpretation is that this observation captured a so-called ‘failed’ or ‘aborted’ state transition (for a more detailed analysis, see J. Wilms et al. (2008)). The accretion disk may have begun to cool and move inwards, softening the spectrum, but the physical mechanism responsible for producing strong variability (e.g., instability at the disk-corona interface (E. Churazov et al. 2001)) failed to fully develop. This anomalously stable intermediate state highlights the complex nature of state transitions and demonstrates that the connection between the accretion geometry and its variability signature is not always straightforward.

4.3. The Hardness-Intensity and Color-Color Diagrams

To more clearly delineate the relationship between the spectral states, we constructed a hardness-intensity diagram (HID) for the entire dataset, shown in Figure 5. Each point corresponds to a 100 s time bin, with its position determined by the total 3-79 keV count rate (Intensity) and the hardness ratio (HR). The data points are color-coded by observation, illustrating how the source explores the diagram over the full 12-year observing baseline.

The hardness-intensity diagram (HID) and flux-flux correlation plots provide fundamental diagnostics for classifying the accretion states of Cygnus X-1. Unlike many transient X-ray binaries that exhibit clear q-shaped hysteresis loops (J. Huang et al. 2025), Cygnus X-1 displays a more persistent behavior (T. M. Belloni & S. E. Motta 2016), spending approximately 50% of its time in the hard state with occasional transitions to softer states. The HID analysis reveals two distinct branches in the intensity-hardness plane (see also E. Meyer-Hofmeister et al. (2020) and M. Böck et al. (2011)). The hard state populates the region with hardness ratios > 0.65 at moderate count rates (200-800 counts/s), while the soft state occupies hardness ratios < 0.35 at higher count rates (800-2500 counts/s). The intermediate state bridges these regimes with hardness ratios between 0.35-0.65. Notably, observation 30302019006 exhibits an anticorrelated behavior with decreasing intensity as hardness increases. We interpret this as a signature of failed state transitions commonly observed in wind-fed systems. The flux-flux diagram provides complementary state classification through the correlation between soft (3-8 keV) and hard (8-79 keV) band count rates. The data follow distinct tracks cor-

responding to different hardness ratios, with the hard state observations clustering along steeper slopes ($H/S > 0.65$) and soft state observations following shallower trajectories ($H/S < 0.35$). The power-law correlation between bands remains approximately linear in log-log space within each state, with correlation indices ranging from 1.2-1.5 for the hard state to 0.8-1.0 for the soft state. The absence of a complete hysteresis loop and the dominance of hard state observations (comprising ~ 13 of the 26 observation epochs) confirm that Cygnus X-1 remains primarily in a low/hard state configuration. State transitions occur on timescales of weeks to months rather than the rapid cycling observed in more active systems, consistent with the system’s persistent nature and its relatively stable mass accretion rate of approximately 0.01-0.1 L_{Edd} (C. J. Skipper et al. 2013).

4.4. Power Spectral Density Analysis

We performed power spectral density (PSD) analysis on all 26 *NuSTAR* observations to characterize the stochastic variability properties across different accretion states. Our approach is complementary to recent comprehensive spectral-timing studies of Cygnus X-1 performed with NICER, which have focused on the rich variability present at lower energies (< 2 keV) where the accretion disk emission dominates (O. König et al. 2024). The PSDs were computed using Welch’s method (P. Welch 1967) with 256-second segments and 50% overlap, providing frequency coverage from 0.01 to 5 Hz. Our frequency range is bounded by the Nyquist limit and large instrument noise below 0.01 Hz. To emphasize characteristic timescales while preserving spectral shape information, we present the PSDs in frequency-weighted form ($f \times \text{PSD}$ vs. f), where peaks directly indicate the frequencies containing maximum variability power.

This frequency band captures an intermediate portion of the well-documented broadband noise spectrum of Cygnus X-1, which is known to span from approximately 10^{-3} Hz to ~ 100 Hz. The broadband power in the hard and intermediate states is typically modeled as a superposition of multiple Lorentzian components (K. Pottschmidt et al. 2003). In our observed band, a single dominant component is evident below 1 Hz. While the onset of a higher-frequency component is visible above this, its characteristic frequency lies beyond our reliable range of analysis. Consequently, to avoid biases from fitting an incomplete feature, we modeled the spectrum exclusively within the 0.01–1 Hz range, employing a single broad Lorentzian function to accurately characterize the dominant, fully-captured noise process.

Figure 7 displays the frequency-weighted Power Spectral Densities (PSDs), color-coded by accretion state.

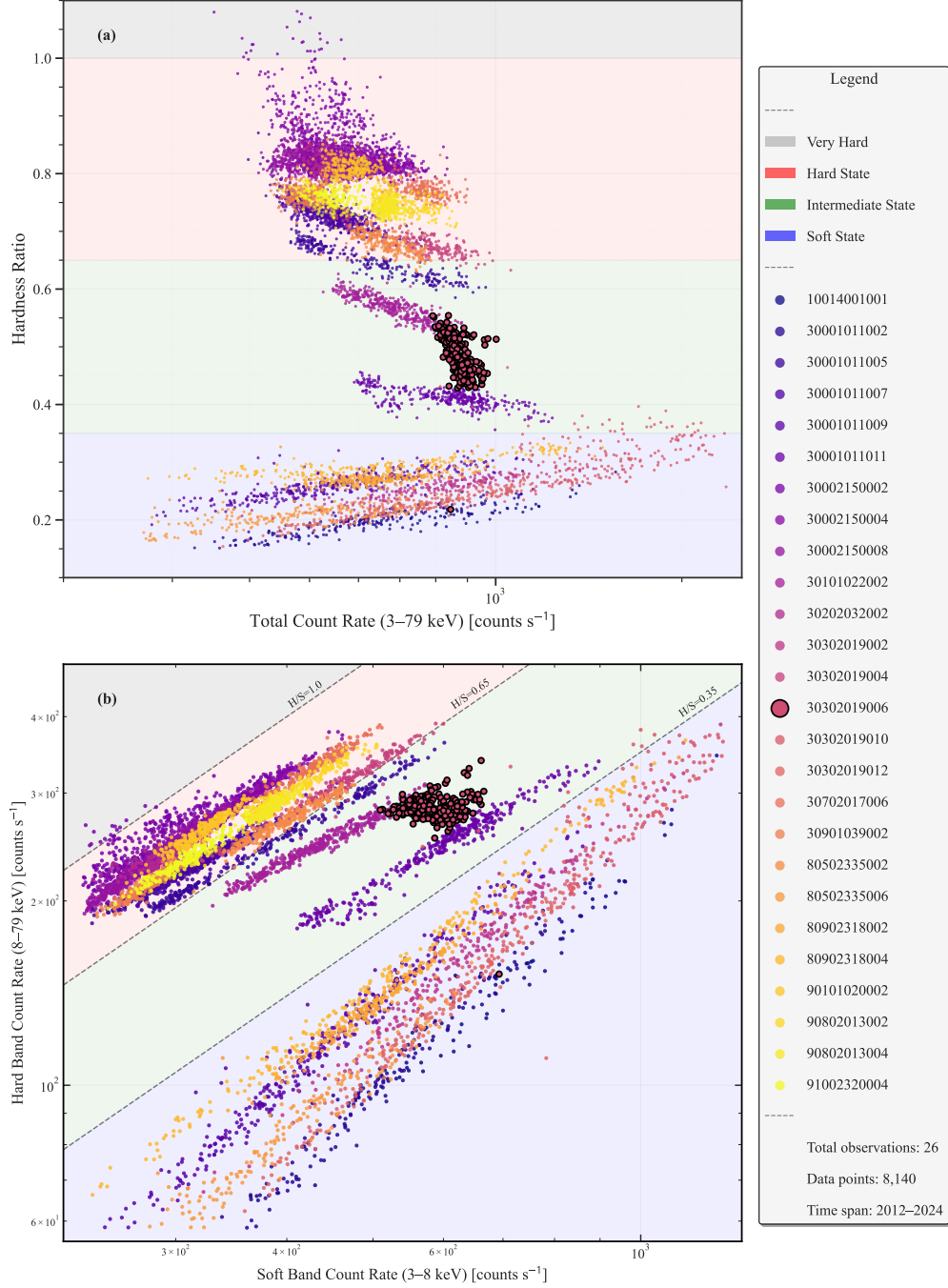


Figure 5. X-ray spectral state classification of Cygnus X-1 from 2012–2024 *NuSTAR* observations. (a) Hardness-intensity diagram showing the hardness ratio and tracing the system’s evolution through spectral states. Background shading indicates the canonical spectral state regions: gray (very hard), red (hard), green (intermediate), and blue (soft). (b) Hard band versus soft band count rate correlation diagram. Diagonal dashed lines indicate constant hardness ratios of 1.0, 0.65, and 0.35, delineating the boundaries between spectral states. Both panels display 8,140 individual observations from 26 distinct epochs (identified by observation IDs in the legend), with symbol colors progressing chronologically from blue to yellow. The bimodal distribution clearly separates the hard state (lower branch) from the soft state (upper branch), with intermediate state transitions connecting the two primary accretion modes. The observation 30302019006 has been highlighted in both panels for showing anticorrelation. The state-dependent flux correlations are consistent with changes in the accretion flow geometry and the relative contributions of the accretion disk and corona/jet components characteristic of this system.

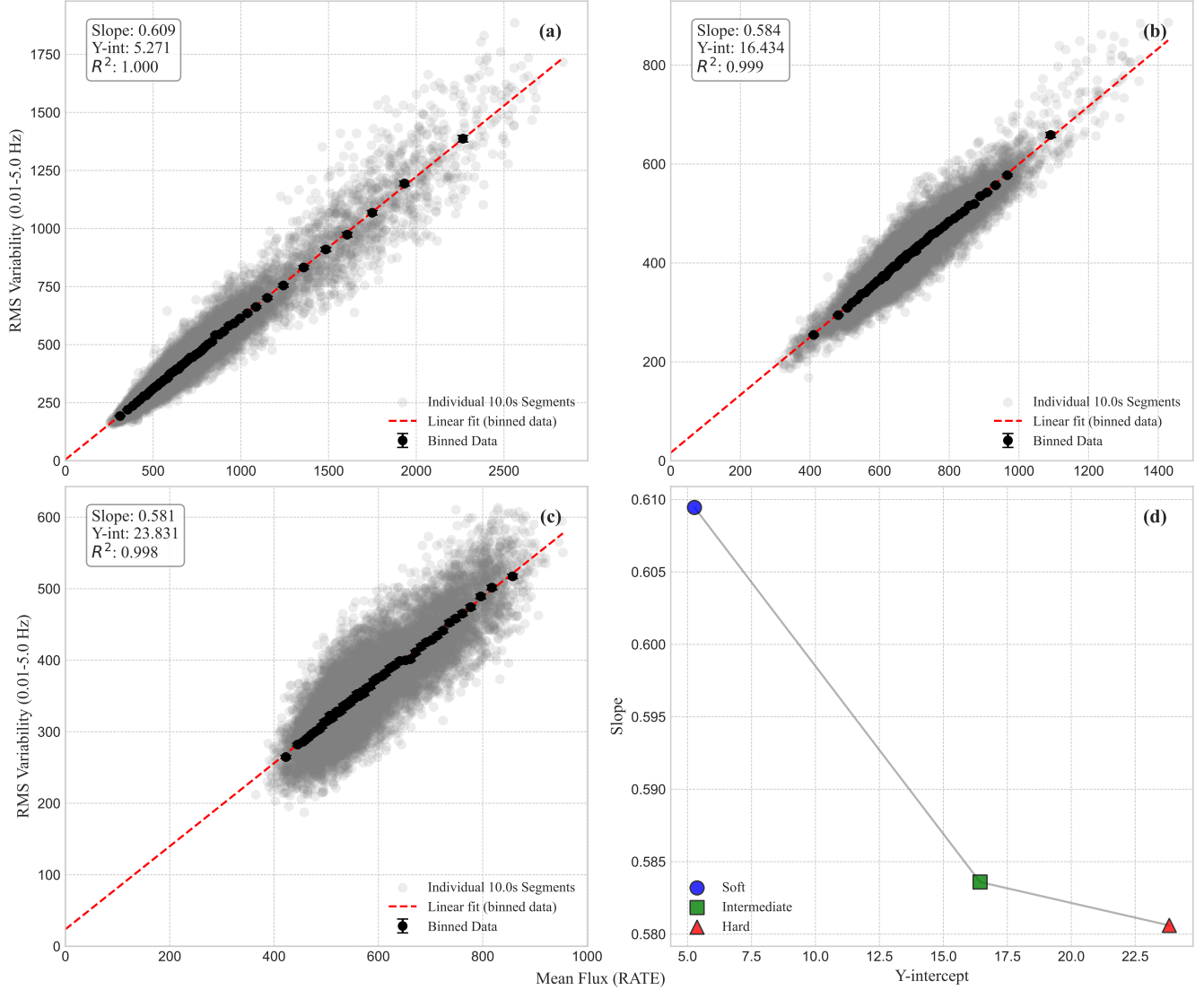


Figure 6. Linear rms-flux correlations in Cygnus X-1 across distinct X-ray spectral states. (a-c) RMS variability (0.01-5.0 Hz) versus mean count rate for the soft state (a), intermediate state (b), and hard state (c). Gray points represent individual 10.0 s segments from the complete dataset, while black points with error bars show binned averages. Red dashed lines indicate the best-fit linear relations to the binned data. The soft state exhibits a steep, nearly linear correlation (slope = 0.609, y-intercept = 5.271, $R^2 = 1.000$), characteristic of disk-dominated emission with minimal coronal contribution. The intermediate state shows a slightly less steep slope (0.584) with substantial y-intercept (16.434, $R^2 = 0.999$), indicating mixed disk-corona contributions with enhanced intrinsic variability. The hard state displays the shallowest slope (0.581) with the largest y-intercept (23.831, $R^2 = 0.998$), consistent with dominant coronal/jet emission and high intrinsic variability amplitude. (d) State-dependent evolution of the rms-flux relation parameters, showing the systematic decrease in slope and increase in y-intercept from soft to hard states. This progression reflects the increasing contribution of variable non-thermal components (corona/jet) relative to the stable thermal disk emission. The observed linear rms-flux scaling across all states, combined with the systematic parameter evolution, provides strong evidence for the multiplicative coupling between mass accretion rate fluctuations and radiative output, modulated by the state-dependent accretion flow geometry.

While individual PSDs (semi-transparent) show significant scatter, the mean trends (bold lines) reveal a clear evolution. The characteristic break frequency, seen as a peak in this representation, systematically shifts to higher values as the source softens. In the hard state, the break is narrowly distributed around a median of 0.050 Hz (see 7a inset). This shifts to a higher and more broadly distributed median of 0.074 Hz in the intermediate state. In contrast, the soft state exhibits a featureless red-noise spectrum with no discernible break. This frequency increase suggests a decrease in the characteristic variability timescale, consistent with a shrinking Comptonizing region as the inner disk moves closer to the black hole.

We assume a truncated geometrically thin-disk model and convert the characteristic frequencies to physical scales using the empirical relation $R_g \sim 6 \left(\frac{50}{m f_{LB}} \right)^{\frac{2}{3}}$ (C. Done et al. 2007) for $m = 21.2 M_\odot$, where R_g is the truncation radius and f_{LB} is the lower break frequency. We observe a roughly linear trend between f_{LB} and R_g , with ranging from $\sim 2 R_g$ in intermediate states to $\sim 5.5 R_g$ in hard states (Figure 7b).

Notably, observation 30302019006 (highlighted with orange edge in Figure 7b) exhibits anomalous behavior despite its intermediate spectral hardness. This observation also displayed anticorrelated hard and soft band fluxes in the color-color diagram (Figure 5b), where typically these bands show positive correlation. We interpret this as a failed state transition: the disk approached the ISCO (evidenced by the high break frequency) but failed to establish the stable soft-state configuration, possibly due to insufficient accretion rate or disruption by the stellar wind. The absence of quasi-periodic oscillations (QPOs) in any observation above 3σ significance is consistent with Cygnus X-1's behavior outside rare transitional episodes (F. A. Fogantini et al. 2025). The systematic evolution of break frequencies and truncation radii demonstrates that geometric reconfiguration of the accretion flow drives both spectral and timing properties in this archetypal black hole system.

4.4.1. Frequency-Dependent Time Lag Analysis

To probe the causal connections between soft and hard X-ray emission, we computed frequency-dependent time lags between the soft and hard bands using cross-spectral analysis. Time lags encode crucial information about the propagation of accretion rate fluctuations and reprocessing geometry in the inner accretion flow. Previous studies (J.-l. Qu & T.-p. Li 2001; K. Pottschmidt et al. 2000) have revealed that hard X-rays consistently lag behind soft X-rays in all states, with lag values depending on frequency and energy separation. During

state transitions, the X-ray lag exhibits significant variability in both its shape and magnitude, often reaching amplitudes substantially larger than those observed during periods of spectral stability.

We calculated cross-power spectra using Welch's method with adaptive window sizes (256-1024 points) to optimize frequency resolution while maintaining adequate statistics. The time lag at each frequency was derived from the phase of the cross-spectrum: $\tau(\nu) = -\phi_{xy}(\nu)/(2\pi\nu)$, where positive lags indicate hard photons lagging soft photons. To ensure reliability, we required coherence > 0.2 and applied 5σ outlier rejection to the lag measurements. The lags were computed in 40 logarithmically-spaced frequency bins spanning 0.01-5 Hz.

Figure 8 shows the resulting lag-frequency spectra, averaged for the hard, intermediate, and soft accretion states. The results reveal a clear and systematic evolution of the time lags as Cygnus X-1 transitions between states.

In the soft state (top panel), the low-frequency hard lag is strongly suppressed, remaining close to zero below 0.5 Hz. This quenching of the lag is a key indicator of a fundamental change in the accretion geometry. It is consistent with the inner edge of the accretion disk extending much closer to the black hole, drastically reducing the size of the hard X-ray emitting corona and, consequently, the light-travel times associated with propagating fluctuations.

As the source transitions to the intermediate state (middle panel), the lag spectrum evolves significantly. The lag remains hard, but its magnitude increases, reaching a maximum of approximately 75 ms near 0.2 Hz before declining towards higher frequencies. This enhancement and shift in the peak lag frequency likely correspond to changes in the structure and dominant timescale of the corona during the state transition. This state also shows the largest variability across frequency ranges, which is possibly indicative of radiation-emitting outflows in the hard state.

Finally, in the hard state (bottom panel), we observe a prominent hard lag (positive values) of approximately 50 ms at the lowest frequencies. This lag systematically decreases with increasing frequency, becoming consistent with zero above ~ 1 Hz. This behavior is the classic signature of propagating accretion fluctuations, where variations originating in the outer regions of the Comptonizing medium travel inwards, modulating the inner regions and imprinting a characteristic frequency-dependent time delay.

At higher frequencies (near 1 Hz), the lag behavior becomes more complex, with both the hard and soft states

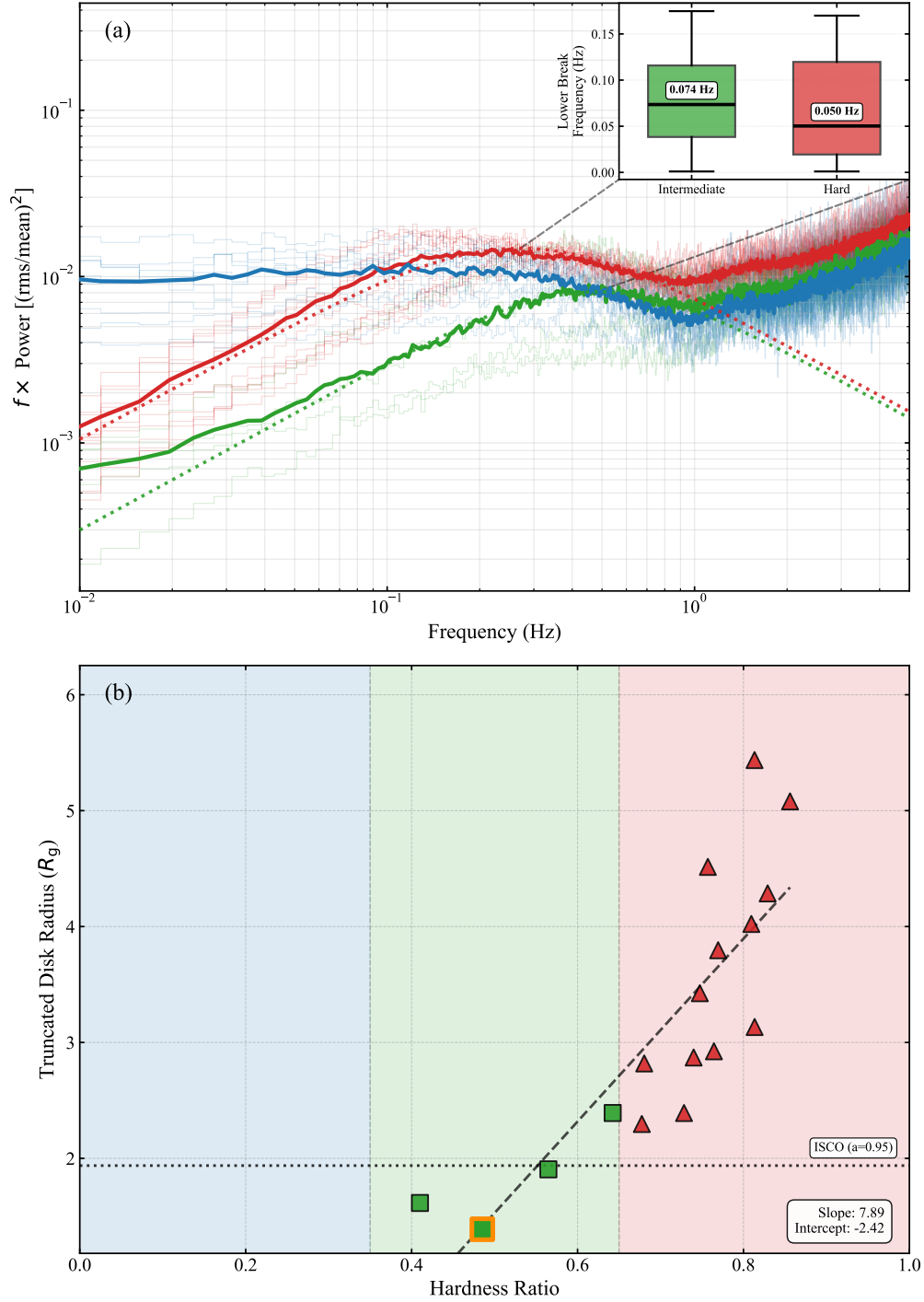


Figure 7. Frequency-weighted power spectral density analysis revealing state-dependent variability characteristics and accretion geometry. (a) $f \times$ PSD curves for all observations color-coded by spectral state. Semi-transparent step functions show individual observations while bold lines indicate state-averaged PSDs. Hard and intermediate states show two characteristic frequencies, the lower ones visible as peaks at ~ 0.050 Hz (hard) and ~ 0.074 Hz (intermediate) and another at ~ 1 Hz. This is absent in the soft state, which is near-constant for frequencies below ~ 1 Hz. Inset: Distribution of lower break frequencies with median values. (b) Truncation radius versus hardness ratio derived from break frequencies assuming a truncated disk model. Background shading indicates spectral state regions. The dashed line shows the linear fit to the relationship. Horizontal dotted line marks the ISCO for spin parameter $a = 0.95$. Observation 30302019006 (orange outline) exhibits anomalously small truncation radius ($< 1R_g$) despite intermediate hardness, coinciding with anticorrelated hard/soft flux behavior indicative of failed state transition.

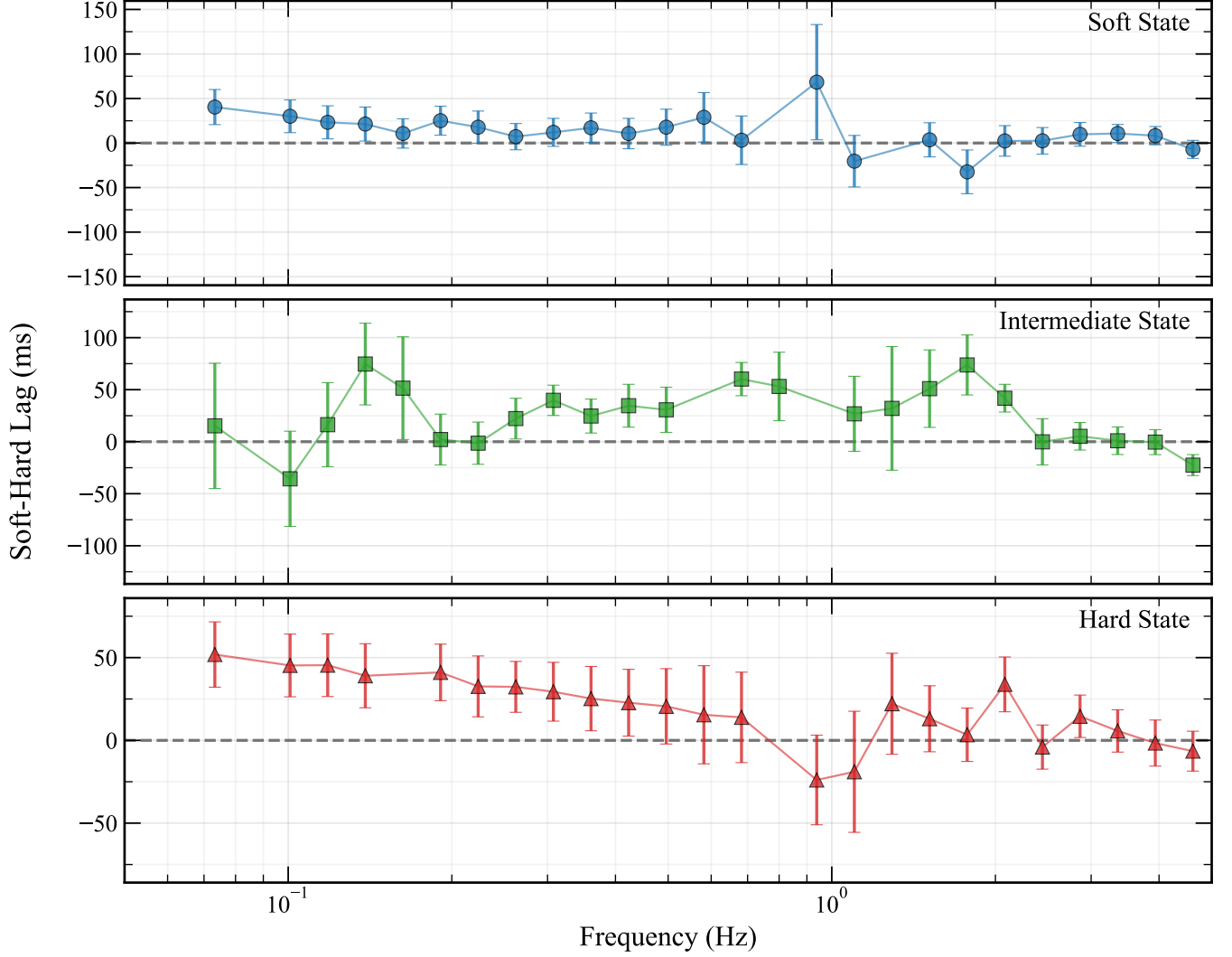


Figure 8. Frequency-dependent soft-hard time lags across spectral states revealing propagation and reprocessing timescales. Top: Soft state shows near-zero lags with slight positive trend, consistent with minimal Comptonization. Middle: Intermediate state exhibits complex frequency-dependent behavior with dramatic variations between observations, transitioning from near-zero (soft-leading) to consistently positive (hard-leading) lags around 0.3 Hz. Bottom: Hard state displays systematic positive lags decreasing with frequency from 20 to 45 ms, characteristic of Comptonization delays in an extended corona. Error bars represent 1σ uncertainties from coherence-weighted cross-spectral analysis with 5σ outlier rejection. The state-dependent lag behavior directly probes the geometric transformation from thin disk (soft) through hybrid (intermediate) to truncated disk plus extended corona (hard) configurations.

showing features that may include a brief turn to a soft lag (negative values). Such features could be indicative of a Compton reverberation signal, where hard coronal photons are rapidly reprocessed by the optically thick accretion disk. Overall, the systematic evolution of the lag spectrum presented here provides strong evidence for the truncated disk/evolving corona model for black hole state transitions.

5. CONCLUSION

This comprehensive NuSTAR timing study establishes Cygnus X-1 as the benchmark system for understanding accretion physics in stellar-mass black holes. Through systematic analysis of 26 observations spanning all spectral states over 12 years, we have uncovered fundamental relationships that constrain theoretical models of disk-corona coupling and state transitions. Our discovery of energy-dependent bimodality in the flux distributions provides a new framework for state classification. The clear separation of peaks in the 8-79 keV band, contrasting with overlapping distributions at lower energies, demonstrates that hard X-rays uniquely trace the geometric reconfiguration between corona-dominated and disk-dominated accretion modes. This finding has immediate practical applications for rapid state identification in current and future X-ray timing missions. The systematic evolution of characteristic frequencies from 0.050 Hz to 0.074 Hz between hard and intermediate states directly maps the inward motion of the disk truncation radius. Combined with the frequency-dependent time lag evolution—from prominent 50 ms hard lags to near-zero lags—these measurements provide the most precise observational constraints to date on the changing extent of the Comptonizing region. The persistence of linear rms-flux relations across all states, with systematically evolving parameters, reveals that multiplicative coupling between accretion fluctuations and radiative output operates universally but is modulated by the state-dependent geometry. The identification of a failed state transition in observation 30302019006 represents a major discovery. This observation’s unique characteristics—anticorrelated band fluxes, anomalously suppressed variability despite intermediate hardness, and an apparent sub-ISCO truncation radius—cannot be explained by standard transition models. We propose this

represents a new transitional pathway where the disk approaches the black hole but fails to establish a stable configuration, possibly due to disruption by the companion’s stellar wind. This finding opens new avenues for theoretical investigation and suggests that state transitions in wind-fed systems may follow fundamentally different evolutionary paths than those in Roche-lobe overflow systems. Our results have broader implications for understanding accretion physics across mass scales. The tight correlations between spectral hardness, characteristic timescales, and variability amplitudes suggest universal scaling relations that may extend from stellar-mass to supermassive black holes. The failed transition phenomenon may explain similar anomalous behavior observed in other systems, including certain changing-look AGN.

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Facilities: NuSTAR

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