

Analysing the high energy emission of the high mass X-ray binary 4U 1700–37 with NuSTAR

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Resumen / 4U 1700–37 es una binaria de rayos X de alta masa acretante por vientos, compuesta por un objeto compacto, probablemente una estrella de neutrones, y una supergigante O6.5 Iaf⁺, HD 153919. A pesar de décadas de observaciones, no se han hallado pulsaciones coherentes ni una estimación firme del campo magnético. Analizamos las propiedades temporales y espectrales en rayos X duros de 4U 1700–37 con *NuSTAR*, buscando pulsaciones y posibles rasgos de dispersión ciclotrón. Se estudió una observación de ~50 ks obtenida entre la salida del eclipse y el periastro, aplicando búsquedas temporales mediante Lomb–Scargle y Z^2 , y modelando el espectro 3–70 keV con diferentes continuos típicos de pulsares acretantes. No se detectaron pulsaciones coherentes entre 100–5000 s; el límite superior de la fracción pulsada es 1.5–1.8 %. El mejor ajuste combina un cuerpo negro y una ley de potencia con corte exponencial, mostrando rasgos débiles cerca de 19.5 keV y 52 keV con una significancia de ~95 %. Estos rasgos podrían asociarse a líneas ciclotrón que implican un campo magnético de $B \approx 1.7 \times 10^{12}$ G. Bajo un régimen de acreción subsónica, el período de equilibrio sería $P_{\text{eq}} \approx 1.9$ ks. Se requieren observaciones más largas con *NuSTAR* para confirmarlo.

Abstract / 4U 1700–37 is a wind-fed high-mass X-ray binary hosting a compact object, likely a neutron star, accreting from the O6.5 Iaf⁺ supergiant HD 153919. Despite decades of observations, no coherent pulsations or firm magnetic field estimates exist. We study the hard X-ray timing and broadband spectrum of 4U 1700–37 using *NuSTAR* to search for pulsations and possible cyclotron resonant scattering features. We analysed a ~50 ks *NuSTAR* observation from eclipse egress to periastron, performing timing searches with Lomb–Scargle and Z^2 statistics, and modelling the 3–70 keV spectrum with several continua used for accreting pulsars. No coherent pulsations were detected between 100–5000 s, setting 90% upper limits on the pulsed fraction of 1.5%–1.8%. The best-fitting model is a blackbody plus cutoff power law, showing weak absorption-like features near 19.5 keV and 52 keV with ~95% significance. These marginal features may indicate cyclotron lines corresponding to a magnetic field of $B \approx 1.7 \times 10^{12}$ G. Within the subsonic settling accretion regime, the expected equilibrium spin period is $P_{\text{eq}} \approx 1.9$ ks. Longer *NuSTAR* exposures are required to confirm these hints.

Keywords / stars: neutron — pulsars: general — X-rays: binaries — X-rays: individual: 4U 1700–37

1. Introduction

4U 1700–37 (hereafter 4U1700) is one of the brightest persistent hard X-ray sources in the Galaxy, classified as a supergiant high-mass X-ray binary (sgHMXB). It was discovered by the *Uhuru* satellite (Jones & Liller, 1973), and its optical counterpart was identified as the O6.5 Iaf⁺ supergiant HD 153919 (Hutchings, 1974). Gaia DR3 astrometry places the system at a distance of ~1.9 kpc within the Sco OB1 association (Gaia Collaboration et al., 2023). The binary completes an eccentric orbit ($e \approx 0.22$) every 3.411581 days with an inclination of $i \approx 66^\circ$ (Rubin et al., 1996), producing deep X-ray eclipses clearly visible in long-term monitoring by *Swift*/BAT and *INTEGRAL* (Walter et al., 2015; Islam & Paul, 2016).

Wind-fed accretion sustains a persistent X-ray luminosity of $L_X \sim (1\text{--}5) \times 10^{36}$ erg s^{−1}, punctuated by occa-

sional flares reminiscent of supergiant fast X-ray transients (SFXTs). Despite extensive searches, no coherent pulsations have been confirmed. Early reports of 24-minute and 97-minute periods from Copernicus and SAS-3 data (Branduardi et al., 1978; Matilsky et al., 1978) were likely instrumental artifacts (Hammerschlag-Hensberge et al., 1979). A tentative 67.4 s pulsation during a bright flare was reported with Tenma (Murakami et al., 1984), but never confirmed. *Chandra* spectroscopy during a major outburst revealed Compton cooling consistent with a neutron star accretor of mass $M_X \simeq 2.4 M_\odot$ (Martinez-Chicharro et al., 2018).

Broad-band spectral studies have reported marginal cyclotron resonant scattering features (CRSFs) at ~16 keV (Bala et al., 2020), ~38 keV (Reynolds et al., 1999), and hints at ~50 keV (Xiao et al., 2024). These features, if real, would allow direct measurement of the neutron star’s magnetic field. In this work, we present a detailed

reanalysis of a ~ 50 ks *NuSTAR* observation to probe the timing and spectral properties of 4U1700, with particular focus on CRSF detectability, continuum modeling, and accretion regime.

2. Observation and Data Reduction

The *Nuclear Spectroscopic Telescope Array* (*NuSTAR*) is a space-based X-ray observatory consisting of two focal plane modules, FPMA and FPMB, equipped with 2×2 solid-state CdZnTe detectors each and operating in the 3–79 keV energy range (Harrison et al., 2013).

NuSTAR observed 4U1700 on 27 January 2022 (obsID 30701023001) with a total exposure of ~ 50 ks. The observation covers $\sim 39\%$ of the orbital period, from post-eclipse to periastron (orbital phases 0.16–0.56). Data were processed using NuSTARDAS within HEASOFT v6.34 and CALDB version 20240229. SAA passages were filtered using SAACALC=3, SAAMODE=STRICT, and TENTACLE=YES. Barycentric corrections were applied using clock file v20240229.

Source and background events were extracted from $60''$ circular regions centered on the source and a clean adjacent chip, respectively. Light curves and spectra were generated using NUPRODUCTS. The *NuSTAR* spectrum is affected by sharp instrumental absorption features from Zn and Cd K-edges in the detectors. These were modeled with EDGE components fixed at 9.3 keV and 26.9 keV, with optical depths $\tau \sim 0.01$ – 0.02 .

3. Results

3.1. Timing Analysis

The 3–79 keV background-subtracted light curve (50 s bins) exhibits significant variability on kilosecond timescales, with count rates increasing by up to a factor of ~ 3 during flares (Fig. 1). We defined soft (3–8 keV) and hard (8–79 keV) bands with comparable total counts. The hardness ratio $(10 - 79)/(3 - 10)$ keV shows a temporal evolution consistent with spectral softening throughout the observation, from out-of-eclipse to periastron passage. To maximize the detectability of possible absorption features, we use the full observational data set to compute the time-averaged spectra. A major flare lasting ~ 8 ks is observed around 70–78 ks, along with shorter ~ 1 ks flares.

Power spectra were computed using 409.6 s segments (Nyquist frequency ~ 10 Hz). Broadband red noise dominates below ~ 0.1 Hz, transitioning to Poisson noise at higher frequencies. We searched for coherent pulsations using the Lomb-Scargle periodogram in the 100–5000 s range, motivated by the expected spin period for wind-accreting sgHMXBs. No significant signal was found above the 3σ level.

Upper limits on the pulsed fraction (PF) were derived using *HENz2vspf* from the *HENDRICS* package (Bacchetti, 2018). By simulating 10^4 pulsations with varying PF and comparing maximum Z_1^2 statistics, we obtained 90% confidence upper limits of 1.45% (FPMA) and 1.8% (FPMB) in the 3–79 keV band.

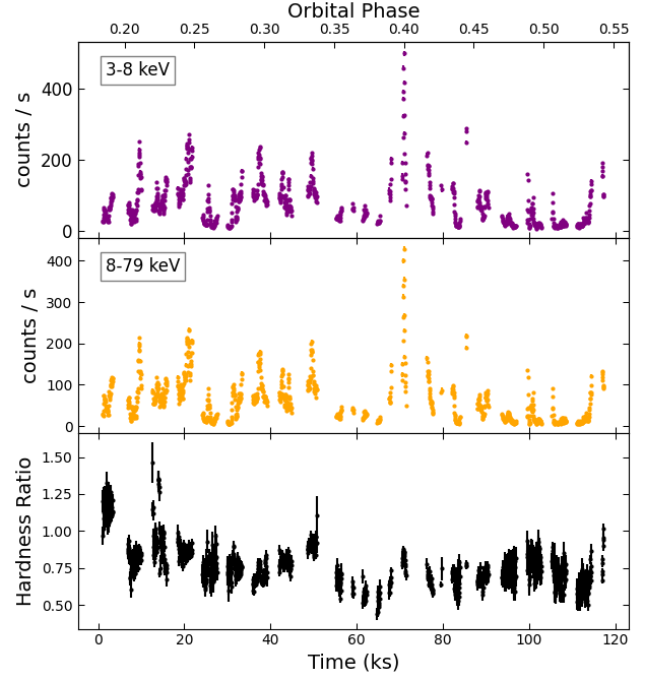


Fig. 1. *NuSTAR* light curves binned at 50 s: 3–8 keV (top), 8–79 keV (middle), and hardness ratio (bottom). Flares lasting ~ 1 – 8 ks are visible.

3.2. Spectral Analysis

Time-averaged spectra in the 3–70 keV range were grouped using the optimal binning scheme of Kaastra & Bleeker (2016) to ensure at least 30 counts per bin, enabling the use of χ^2 statistics. Spectral fitting was performed with XSPEC v12.14.1. Five continuum models were tested: BBODY+CUTOFFPL, BBODY+NTHCOMP, THCOMP*BBODY, BBODY+POWERLAW*HIGHECUT, and NPEX (Mihara et al., 1995). Absorption was modeled using PCFABS with Anders & Grevesse (1989) abundances and Verner et al. (1996) cross-sections. A Gaussian component accounted for the Fe K α emission line near 6.4 keV. Cross-calibration constants between FPMA and FPMB remained within the expected 5% range (Madsen et al., 2015).

The best-fitting model is BBODY+CUTOFFPL, yielding $\chi^2/\text{dof} = 541.1/434$. The absorption column is $N_{\text{H}} = (18 \pm 1) \times 10^{22} \text{ cm}^{-2}$ with a covering fraction $f_{\text{cov}} = 0.44 \pm 0.02$. The blackbody component has a temperature $kT_{\text{bb}} = 1.64^{+0.03}_{-0.02} \text{ keV}$ and normalization $K_{\text{bb}} = (43 \pm 3) \times 10^{-4}$. The power-law has a photon index $\Gamma = 1.05 \pm 0.03$, cutoff energy $E_{\text{cut}} = 17.1 \pm 0.4 \text{ keV}$, and normalization $K_{\text{pl}} = 0.18 \pm 0.01$. The Fe K α line is centered at $E = 6.318^{+0.006}_{-0.007} \text{ keV}$ with width $\sigma = 0.019^{+0.01}_{-0.009} \text{ keV}$ and normalization $(12.4 \pm 0.4) \times 10^{-4} \text{ photons cm}^{-2} \text{ s}^{-1}$.

Residuals from all tested continua show absorption-like features above ~ 20 keV, which we interpret as candidate CRSFs. In Fig. 2, we present the spectrum together with the residuals corresponding to the best-fitting continuum model, while the additional panels illustrate the improvement obtained after the inclusion of

the GABS components.

We modeled these features using two multiplicative GABS components in XSPEC, and systematically explored the parameter space with the STEPPAR command. The line centroids were scanned from 10 to 70 keV in steps of 0.5 keV, Gaussian widths from 0.5 to 5 keV in steps of 0.1 keV, and the line strength was initially fixed at 1 keV to ensure stable convergence and to avoid degeneracies during the initial grid search. This procedure identified significant CRSF candidates at ~ 19.5 keV and ~ 52 keV, with F-test p-values of 0.002 and 3.4×10^{-5} , respectively.

The best-fitting parameters are $E_1 = 19.5^{+0.8}_{-0.9}$ keV, $\sigma_1 = 4 \pm 2$ keV, and $\tau_1 = 0.3^{+0.6}_{-0.2}$ for the lower-energy feature, and $E_2 = 52^{+4}_{-5}$ keV, $\sigma_2 = 15^{+3}_{-5}$ keV, and $\tau_2 = 10^{+9}_{-7}$ for the higher-energy feature, improving the fit to $\chi^2/\text{dof} = 495/428$ (see Fig. 2).

The significance of the CRSFs was further assessed through 10^5 spectral simulations using XSPEC SIMFTEST, following Hurkett et al. (2008). The features at 19.5 keV and 52 keV yield significances of 1.7σ and 1.64σ , respectively, when adopting our preferred continuum. For simpler continua (e.g., a pure CUTOFFPL), the significances exceed 3σ in archival datasets. Although these results show some degree of model dependence, the absorption-like residuals near ~ 19.5 keV and ~ 52 keV persist at consistent energies across a broad range of tested continua. This stability in energy suggests a physical origin rather than fitting artifacts, highlighting the importance of inspecting residual structures in addition to relying on global fit statistics. Deeper *NuSTAR* observations, or future hard X-ray missions, will be required to confirm the presence of CRSFs in this system at a significance level above 3σ .

4. Discussion

4.1. Comparison with Previous Studies

It has been reported that strong flux variability occurs on timescales of kilo-seconds in 4U1700, commonly attributed to clumpy wind accretion from the donor star. Our analysis confirms this behaviour, with flares ranging from a quiescent flux of $\sim 2 \times 10^{-9}$ erg cm $^{-2}$ s $^{-1}$, consistent with van der Meer et al. (2005), to peaks of $\sim 1 \times 10^{-8}$ erg cm $^{-2}$ s $^{-1}$, in line with other sgHMXB (see e.g., Odaka et al., 2013; García et al., 2018; Saavedra et al., 2022). Our CRSF energies are in good agreement with Bala et al. (2020) (~ 16 keV) and Xiao et al. (2024) (~ 50 keV). The ~ 38 keV feature reported by Reynolds et al. (1999) is not detected in the primary observation but is recovered at 2.93σ in archival obsID 30101027002 using BBODY+CUTOFFPL. Conversely, using only CUTOFFPL on the archival data yields a ~ 15.8 keV CRSF at $> 3\sigma$ and a Fe K β line, but BBODY+CUTOFFPL is strongly preferred ($p \sim 5 \times 10^{-31}$ via F-test). This demonstrates the critical importance of continuum modeling in CRSF detection.

The lack of pulsations is consistent with all prior studies. The flaring behaviour with no associated changes in hardness aligns with wind accretion from a clumpy stellar wind (Xiao et al., 2024).

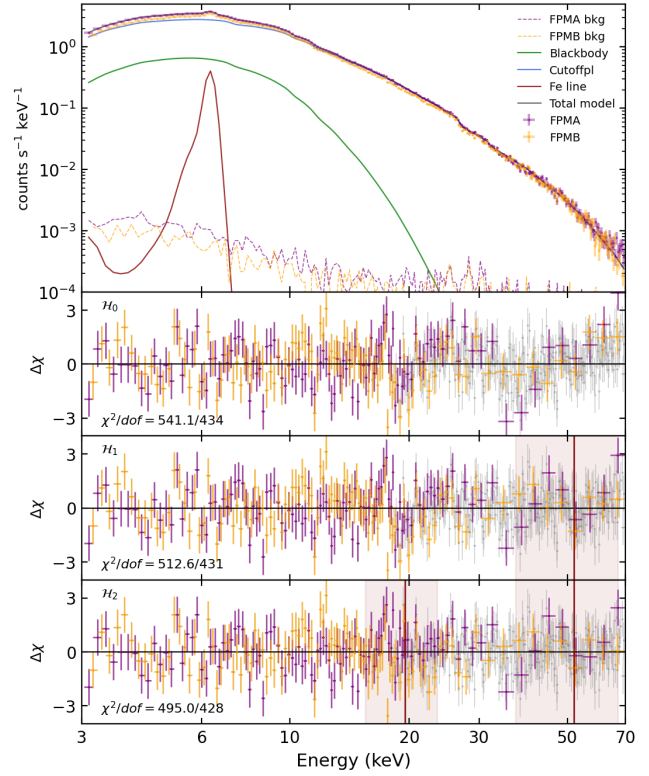


Fig. 2. *Top panel:* FPMA (orange) and FPMB (purple) background-subtracted spectra of 4U1700, together with the best-fitting continuum model. Background spectra are shown with dashed lines. *Lower panels:* Residuals corresponding to the progressive inclusion of cyclotron absorption components. The first residual panel shows the baseline continuum including the Fe line contribution ($\mathcal{H}_0$). The following panels illustrate the inclusion of one GABS component ($\mathcal{H}_1$) at ~ 50 keV and two GABS components ($\mathcal{H}_2$), with an additional feature at ~ 20 keV. Vertical maroon bands mark the candidate CRSFs, indicating their centroid energies and widths. The total χ^2 and degrees of freedom are reported in the bottom-left corner of each panel. For clarity, the data were rebinned for visualization purposes.

4.2. Magnetic Field and Accretion Regime

Adopting $E_{\text{cyc}} = 19.5$ keV as the fundamental Landau level ($n = 1$), and considering redshift zero ($z_g = 0$):

$$\frac{B}{10^{12} \text{ G}} = (1 + z_g) \left(\frac{E_{\text{cyc}}}{11.57 \text{ keV}} \right) \simeq 1.68^{+0.08}_{-0.07}.$$

The ~ 52 keV feature ($E_2/E_1 \approx 2.67$) may originate from a different region of the accretion column rather than representing a harmonic of the ~ 19.5 keV feature. Nevertheless, given the substantial uncertainties in the measured centroid energies, a harmonic relationship cannot be confidently ruled out.

The unabsorbed flux in 3–70 keV yields a luminosity of $L_X = (1.69 \pm 0.01) \times 10^{36}$ erg s $^{-1}$ (assuming a distance of 1.9 kpc). This luminosity is below the threshold $L_X \lesssim 4 \times 10^{36}$ erg s $^{-1}$, allowing application of the quasi-spherical subsonic settling accretion model for slowly rotating magnetized NSs Shakura et al. (2012). In this

regime, accreting material from the stellar wind settles subsonically onto the rotating magnetosphere, forming an extended quasi-static shell. The shell mediates angular momentum removal from the neutron star via large-scale convective motions during spin-down episodes, with the accretion rate through the shell limited by the plasma’s ability to enter the magnetosphere. This subsonic settling occurs for moderate accretion rates: $\dot{M}_{16} < 3.7\mu_{30}^{1/4}$, where $\dot{M}_{16} \equiv \dot{M}/10^{16} \text{ g s}^{-1}$ is the normalized mass accretion rate, and $\mu_{30} \equiv \mu/10^{30} \text{ G cm}^3$ is the normalized magnetic dipole moment ($\mu = BR_{\text{NS}}^3/2$, with B the surface equatorial dipole magnetic field and R_{NS} the NS radius).

Adopting $B \approx 1.69 \times 10^{12} \text{ G}$ and a canonical $R_{\text{NS}} = 10 \text{ km}$ gives $\mu_{30} \simeq 0.84$. The resulting critical accretion rate is $\dot{M}_{16,\text{crit}} \simeq 3.5$. The observed accretion rate, derived from the luminosity as $\dot{M}_{16} \sim 10L_{\text{X}}/c^2 \simeq 1.88$, satisfies $\dot{M}_{16} < \dot{M}_{16,\text{crit}}$ and is well below the supersonic Bondi–Hoyle–Lyttleton rate, confirming the applicability of the subsonic settling model.

The equilibrium spin period predicted by the model is

$$P_{\text{eq}} \simeq 940 \text{ s } \mu_{30}^{12/11} \left(\frac{P_b}{10 \text{ d}} \right) \dot{M}_{16}^{-4/11} v_8^4,$$

where P_b is the orbital period and $v_8 = v_w/10^8 \text{ cm s}^{-1}$ is the normalized stellar wind velocity. Using $P_b = 3.41 \text{ d}$ and $v_w = 1750 \text{ km s}^{-1}$ ($v_8 = 17.5$) for the supergiant companion HD 153919 (Clark et al., 2002) yields $P_{\text{eq}} \simeq 1.9 \pm 0.1 \text{ ks}$.

This places 4U1700 in the upper-left region of the Corbet diagram (Corbet, 1986), consistent with wind-accreting sgHMXBs. The absence of pulsations near P_{eq} may result from unfavorable viewing geometry, low pulsed fraction, or intermittent emission as observed in LS +61°303 (Weng et al., 2022).

5. Conclusions

Our findings from the analysis of a $\sim 50 \text{ ks}$ NuSTAR observation of 4U1700 can be summarized as follows:

- No coherent pulsations were detected in the NuSTAR light curves with significances above 3σ . We place upper limits on the pulsed fraction for FPMA and FPMB, resulting in 1.5% and 1.8%, respectively.
- Hints of CRSFs were found at $\sim 19.5 \text{ keV}$ and $\sim 52 \text{ keV}$, with marginal detection levels of $\sim 95.5\%$ and $\sim 94.5\%$, respectively. These putative CRSFs energies are consistent with previous studies (Bala et al., 2020; Xiao et al., 2024).
- The CRSF at $\sim 38 \text{ keV}$ reported by Reynolds et al. (1999) was not detected in the time-averaged spectra. However, rate-resolved spectroscopy revealed a CRSF at $\sim 38\text{--}40 \text{ keV}$, and analysis of an archival NuSTAR observation revealed a CRSF at $\sim 39 \text{ keV}$.

- Applying the framework of subsonic accretion onto NSs, we estimate the equilibrium period of the pulsar to be $P_{\text{eq}} \approx 1.9 \text{ ks}$, placing 4U1700 well inside the supergiant HMXB region in the Corbet diagram.

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