

Probing the orbit of the high-mass X-ray binary 4U 1700-37 with NICER

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Resumen / Presentamos los resultados del análisis de una campaña de monitoreo del sistema binario de rayos X de alta masa 4U 1700-37, que consta de 15 observaciones de la misión NICER realizadas entre Agosto y Septiembre de 2019. La curva de luz en el rango de 0.2–12 keV muestra intensas erupciones, una característica común en estos sistemas de acreción por viento. No se detectaron pulsaciones coherentes a un nivel de significancia de 3σ en el rango de frecuencias de 2×10^{-4} –0.01 Hz. Los espectros promediados en el tiempo se pueden describir mediante un modelo de tres componentes: un componente de emisión suave, un componente de emisión dispersada y un componente de emisión directa, cada uno representado por una ley de potencia con índices de fotones idénticos entre sí pero con flujos y columnas de absorción independientes. Durante las fases de ingreso y egreso del eclipse, se detectan líneas de emisión de fluorescencia y recombinación, incluyendo las líneas Fe K α (6.4 keV) y K β (7.1 keV), así como las líneas Mg K α , Si K α y S K α a energías por debajo de 3 keV. También reportamos evidencia tentativa de una línea de Ni a 8.3 keV, no reportada previamente. La columna de absorción del componente de ley de potencia de mayor energía se anticorrelaciona con los cocientes de flujo línea-continuo de Fe y Ni, lo que sugiere que estas líneas se producen cerca del objeto compacto.

Abstract / We present the results from a NICER monitoring campaign of the high-mass X-ray binary 4U 1700-37, consisting of 15 observations made between August and September of 2019. The 0.2–12 keV lightcurve reveals flares, a common feature in this wind-fed accreting systems. No coherent pulsations are detected up to a 3σ significance level in the 2×10^{-4} –0.01 Hz frequency range. The time-averaged spectra are well described by a three-component model: a soft component, a scattered component, and a direct component, each represented by a power law with identical photon indices but independent absorption columns and fluxes. During eclipse ingress and egress orbital phases, prominent fluorescence and recombination emission lines are detected, including Fe K α (6.4 keV) and K β (7.1 keV) lines, as well as Mg K α , Si K α , and S K α lines at energies below 3 keV. We also report tentative evidence of a previously unreported Ni line at 8.3 keV. The absorption column of the higher energy power-law component anticorrelates with Fe and Ni line-to-continuum flux ratios, consistent with these lines being produced close to the compact object.

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

1. Introduction

4U 1700-37 (hereafter 4U1700) is a transient, eclipsing high-mass X-ray binary (HMXB) initially identified by the *Uhuru* satellite in 1970 (Jones & Liller, 1973). Its optical companion, the runaway O6.5Iaf⁺ supergiant HD 153919, was recognized soon after (Hutchings, 1974), leading to its classification as a supergiant X-ray binary (sgHMXB) (Chaty et al., 2008; Coleiro et al., 2013). Astrometric data from Gaia DR3 place 4U1700 at a distance of approximately 1.9 kpc within the Sco OB1 association (Gaia Collaboration et al., 2023). The system ranks among the ten brightest Galactic hard X-ray sources, as monitored by *INTEGRAL* and *Swift*/BAT (Walter et al., 2015). The binary system follows an eccentric orbit ($e \approx 0.22$) with a period

of 3.412 days and an inclination of $\approx 66^\circ$ (Rubin et al., 1996), resulting in prominent X-ray eclipses and modulations evident in its light curves (Islam & Paul, 2016).

Previous studies reported tentative pulsations at periods of 24 and 97 minutes from *Copernicus* and *SAS-3* observations (Branduardi et al., 1978; Matilsky et al., 1978), though the 97-minute period was later suggested to be an instrumental artifact (Hammerschlag-Hensberge et al., 1979). A possible 67.4 s pulsation was noted during a significant flare observed by *Tenma* (Murakami et al., 1984; Simpson, 1984), but subsequent observations have not confirmed these periodicities. *Chandra* spectroscopy during a major flare indicated Compton cooling consistent with a neutron star accretor of mass $M_X \approx 2.4, M_\odot$ (Martinez-Chicharro et al., 2018). Additionally, broadband spectral analysis using *NuS-*

TAR and *AstroSat* data revealed marginal evidence of cyclotron resonance scattering features (CRSFs) at ~ 16 keV (Bala et al., 2020).

In this work, we present the results of a detailed temporal and spectral X-ray analysis obtained from 15 *NICER* observations. In Section 2 we present the observation details and data reduction procedure. In Section 3 we show the temporal and spectral results we obtained. In Section 4 we analyse in detail our results, constraining system properties by analysing the evolution of the model parameters along 4U1700’s orbit. Finally, in Section 5 we summarize our main findings.

2. Observation and Data Analysis

2.1. Swift/BAT data

The Swift Burst Alert Telescope (BAT; Barthelmy et al. 2005) is a wide-field, hard X-ray telescope designed to detect and locate gamma-ray bursts (GRBs), which is part of the Swift observatory (Krimm & Swift Team, 2004), a multi-wavelength observatory launched by NASA in 2004. The BAT uses a coded aperture mask to achieve a large field of view and high sensitivity in the 15-150 keV energy range.

In this paper we consider the full orbital light curve of 4U1700 available up to December 1st, 2024 in the Swift/BAT service*, a public website where more than 1000 light curves of hard X-ray sources are available, spanning close to 20 years of continuous data.

2.2. NICER data

The *NICER* telescope observed 4U1700 from August 4 to September 29, 2019, on 15 occasions with exposures of up to ~ 8 ks, with obsIDs ranging from 2617010101 to 2617010115. We processed the data using the *NICER* data analysis software (*nicer*das) available within the HEASOFT v6.34 package. The observation files were reduced using *nicer*l2 with the CALDB v.20240206 calibration files. To extract *NICER* light curves and spectra, we employed the *nicer*l3. To account for the background contribution, we utilized the 3C50 model (Remillard et al., 2022), which subtracts the non-X-ray background (NXB) by accounting for environmental factors such as cosmic ray (CR) contributions, geomagnetic activity, and solar wind conditions, as derived from real-time space weather data. We obtained background subtracted light curves and spectra from the different observations in the energy range of 0.3–12 keV with a temporal binning of 10 s.

3. Results

3.1. Temporal analysis

We extracted *NICER* light curves in three energy bands: soft (0.3–2 keV), medium (2–5 keV), and hard (5–10 keV), with 10 s binning. We constructed a normalized

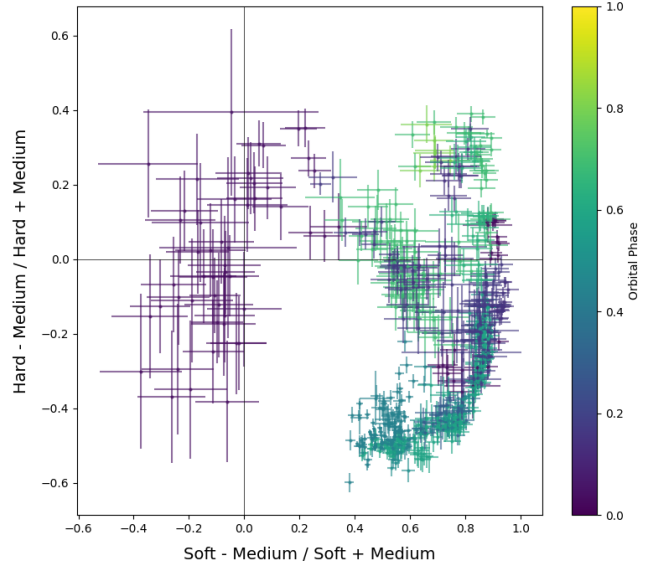


Fig. 1. Color-color diagram of 4U1700. The horizontal axis shows the normalized ratio between the soft (0.3–2 keV) and medium (2–5 keV) energy bands light curves. The vertical axis displays the normalized ratio between the hard (5–10 keV) and medium (2–5 keV) energy band light curves. The color gradient represents the orbital phase, with 0 corresponding to mid-eclipse phase.

color-color diagram (see Fig. 1), using a color gradient to indicate the orbital phase, where phase 0 corresponds to the mid-eclipse phase, defining each energy band as

$$HR_i = \frac{\Delta E_l - \Delta E_n}{\Delta E_l + \Delta E_n}. \quad (1)$$

In Fig. 1, the color-color diagram shows a smooth clockwise evolution that softens the source towards maximum emission, followed by counter-clockwise hardening as the system approaches eclipse.

To explore 4U1700 temporal variability, we extracted power spectra (0.2–12 keV) from *NICER* data with 0.05 s resolution, which corresponds to a Nyquist frequency of 10 Hz. Along the orbit, the power spectra are dominated by broadband noise up to 0.1 Hz, followed by Poisson noise at higher frequencies. We used the Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982) to search for pulsations between 100–5000 s in the *NICER* data, but we found no candidates that exceeded the 3σ detection level.

3.2. Spectral analysis

We conducted the X-ray spectral analysis in the 0.5–10 keV range. Time-averaged spectra were binned using an optimal binning method ensuring at least 30 counts per bin (Kaastra & Bleeker, 2016), and with the 3C50 background model. Uncertainties were derived from converged Markov Chains of length 10^5 , with walkers equal to 16 times the number of free parameters, using the Goodman-Weare algorithm. We modelled the *NICER* time-averaged spectra of 4U1700 with three power-law components (soft, scattered and direct) with identical photon indices modified individually by local and inter-

*<https://swift.gsfc.nasa.gov/results/transients/4U1700-377/>

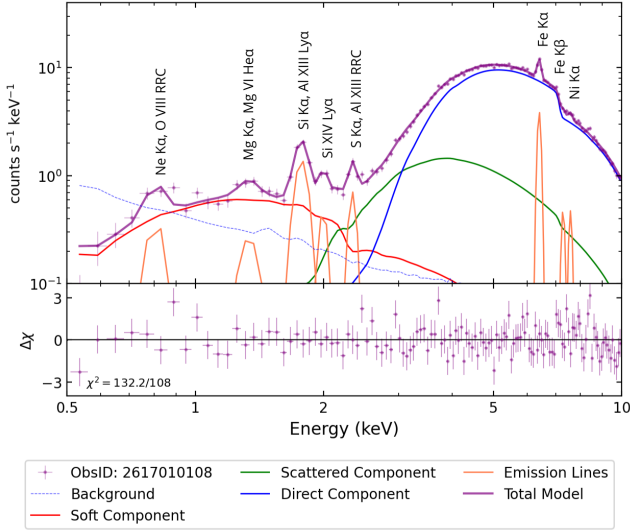


Fig. 2. NICER time-averaged spectra of 4U1700. The upper panel shows the observed data and fitted model components: the NICER data and total model are shown in purple, individual power-law components in red, green and blue, and emission lines in coral. The 3C50 background model is shown with a dashed line. The lower panel displays the normalized residuals, the best value of the goodness-of-fit statistic, and the number of degrees of freedom.

stellar absorption, plus narrow features like Fe K α line at ~ 6.4 keV and wind-shock emission lines (eg, Mg K α at ~ 1.8 keV), more evident near the eclipse (see Fig. 2).

4. Discussion

The *NICER* campaign reveals a picture that is fully consistent with wind accretion onto a compact object embedded in a structured, clumpy outflow from the O supergiant companion. In the 0.3–12 keV light curves we see flares that are naturally explained by sporadic capture of dense wind clumps (e.g., García et al., 2018; Fogantini et al., 2023; Saavedra et al., 2022), while the broad-band aperiodic noise dominating the power spectra up to ~ 0.1 Hz points to stochastic variability in the accretion rate. The absence of significant coherent pulsations (down to a 3σ level in the 2×10^{-4} – 10^{-2} Hz range) may indicate either a spin period outside our searched window, a low pulsed fraction due to multiple scattering in an optically thick local medium, or a combination of geometric smearing and variable partial covering that dilutes the pulsed signal. We note that previous claims of pulsations in 4U1700 have remained unconfirmed (e.g. Murakami et al., 1984; Simpson, 1984), and our results are compatible with that historical picture. Combined with previous estimates of a $\sim 2.4 M_{\odot}$ compact object mass and tentative cyclotron features at higher energies, this supports the interpretation of 4U1700 as an obscured, wind-fed neutron star system in which any spin modulation is strongly diluted by scattering and absorption.

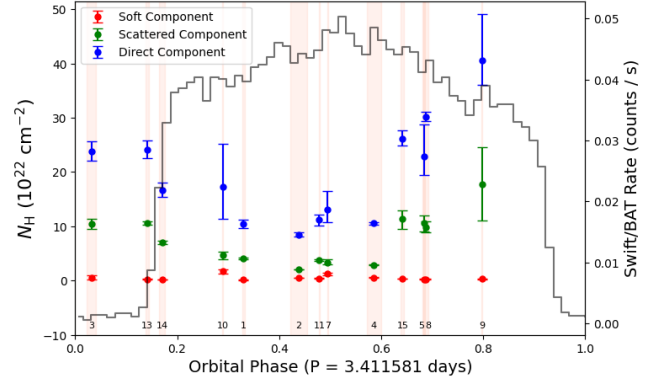


Fig. 3. Folded *Swift*/BAT light curve of 4U 1700 using 64 orbital-phase bins, folded with $P = 3.411581$ d and reference epoch MJD 57446.5. The black stepped curve (right y-axis) shows the folded BAT count rate. Vertical coral bands mark the *NICER* observation used in this work. Orbital phase is shown on the horizontal axis. Colored points with error bars indicate N_H from spectral fits per phase bin: red for the soft component, green for the scattered component, and blue for the direct component.

Orbital geometry and wind structure

The phase-resolved behaviour of the absorption traces the large-scale structure of the wind and the system geometry. As shown in Fig. 3, the maximum in the *Swift*/BAT folded light curve occurs at $\phi \approx 0.56$, whereas the minimum column density for the direct component is found at $\phi \approx 0.44$ (obsID 2617010102). The phase offset implies a periastron angle of $\omega \approx 33^\circ$, in agreement with the value inferred from high-resolution UV spectroscopy (Hammerschlag-Hensberge et al., 2003). In a wind-fed system, this configuration naturally produces a mismatch between flux and absorption extrema: the hard X-ray flux peaks where the accretion rate is enhanced by the smaller orbital separation and lower relative wind velocity, while the line of sight column is minimized slightly earlier in phase, before the compact object enters the denser accretion wake and photoionization tail trailing it. The smooth evolution seen in the color-color diagram, ordered by orbital phase (Fig. 1), supports this interpretation. The combined use of the *Swift*/BAT folded profile and the *NICER*-derived N_H evolution therefore provides an independent consistency check on the orbital solution and confirms that the accretion wake and photoionisation tail dominate the phase-dependent absorption.

Origin of the spectral components and lines

The *NICER* time-averaged spectra require three power-law components with identical photon indices and distinct fluxes and absorption columns. This widely used phenomenology in obscured sgHMXBs can be interpreted as: (i) a soft, lightly absorbed component produced by scattering of the intrinsic continuum in an extended, lower-density medium; (ii) a more absorbed “scattered” component arising in material closer to the compact object (e.g., the base of the accretion wake);

and (iii) a heavily absorbed direct component that samples the densest structures along the line of sight. Similar multi-component continua have been reported in other obscured systems, where the least absorbed component is associated with large-scale scattering in the stellar wind, the intermediate component traces the inner accretion wake, and the most absorbed continuum provides a direct view of the compact object through dense, inhomogeneous structures. In this framework, the phase dependence of the three columns in 4U1700 indicates that the densest material is concentrated in a confined region close to the compact object, rather than being distributed uniformly throughout the wind.

We also report tentative evidence for a feature at ~ 8.3 keV. Within our energy resolution and calibration systematics, this is compatible with Ni K β fluorescence (expected near 8.26 keV) and/or blends including FeXXVI Ly β . Given the limited leverage of *NICER* at the highest energies and possible background-model uncertainties. Deeper exposures and future high-resolution observations with missions such as XRISM Resolve would help confirm the nature of the feature and place tighter constraints on the Ni/Fe abundance ratio.

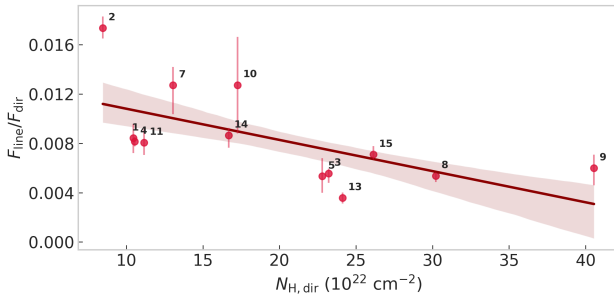


Fig. 4. Fe K α line flux normalized to the 7–12 keV continuum flux as a function of the direct component column density $N_{\text{H,dir}}$.

The Fe and Ni fluorescence properties correlate with $N_{\text{H,dir}}$ (Figs. 3 and 4): while the absolute line fluxes increase with column density, the line-to-continuum flux ratio shows a strong anticorrelation ($r_s = -0.7$, $p = 7.88 \times 10^{-3}$). This behaviour reflects the increasing attenuation of the direct continuum at high $N_{\text{H,dir}}$ and is consistent with the fluorescent material being associated with the densest absorbing regions (Torrejón et al., 2010).

5. Conclusions

- *NICER* light curves show strong, stochastic flaring consistent with clumpy wind accretion; power spectra are dominated by broad-band noise and reveal no coherent pulsations down to a 3σ level in the 2×10^{-4} – 10^{-2} Hz range.
- Time-averaged spectra are well described by three quasi-independent power-law components plus narrow emission lines. Each component can be put in

correspondance with a physical component in the environment of obscured sgHMXBs.

- Fluorescence and recombination lines (Fe K α , K β ; Mg, Si, S) strengthen around eclipse ingress/egress, indicating an extended reprocessing region. Their behaviour with absorption supports a dominant reprocessor located close to the compact object.
- The phase offset between the *Swift*/BAT flux maximum ($\phi \approx 0.56$) and the minimum absorption ($\phi \approx 0.44$) implies a periastron angle $\omega \approx 33^\circ$, consistent with previous UV-based estimates (Hammerschlag-Hensberge et al., 2003).
- A tentative feature at ~ 8.3 keV may correspond to Ni K β and/or FeXXVI Ly β ; confirmation requires deeper high-energy coverage.

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