The Symbiotic X-ray binaries Sct X-1, 4U 1700+24 and IGR J17329-2731

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ABSTRACT
Symbiotic X-ray binaries are systems hosting a neutron star accreting form the wind of a late type companion. These are rare objects and so far only a handful of them are known. One of the most puzzling aspects of the symbiotic X-ray binaries is the possibility that they contain strongly magnetized neutron stars. These are expected to be evolutionary much younger compared to their evolved companions and could thus be formed through the (yet poorly known) accretion induced collapse of a white dwarf. In this paper, we perform a broad-band X-ray and soft γ-ray spectroscopy of two known symbiotic binaries, Sct X–1 and 4U 1700+24, looking for the presence of cyclotron scattering features that could confirm the presence of strongly magnetized NSs. We exploited available Chandra, Swift, and NuSTAR data. We find no evidence of cyclotron resonant scattering features (CRSFs) in the case of Sct X–1 but in the case of 4U 1700+24 we suggest the presence of a possible CRSF at ~16 keV and its first harmonic at ~31 keV, although we could not exclude alternative spectral models for the broad-band fit. If confirmed by future observations, 4U 1700+24 could be the second symbiotic X-ray binary with a highly magnetized accreter. We also report about our long-term monitoring of the last discovered symbiotic X-ray binary IGR J17329–2731 performed with Swift/XRT. The monitoring revealed that, as predicted, in 2017 this object became a persistent and variable source, showing X-ray flares lasting for a few days and intriguing obscuration events that are interpreted in the context of clumpy wind accretion.

Key words: accretion: accretion discs; X-rays: stars; X-rays: binaries; stars: neutron; stars: massive; X-rays: individual: Sct X–1; X-rays: individual: 4U 1700+24; X-rays: individual: IGR J17329–2731.

1 INTRODUCTION
Symbiotic X-ray binaries (SyXBs) are rare low mass X-ray binaries (LMXBs) hosting a red giant and (in most cases) a neutron star (NS) accreting from the slow wind of its companion. Only five1 SyXBs are known so far (Masetti et al. 2006, 2007b,a; Nucita et al. 2007; Corbet et al. 2008; Nespoli et al. 2008; Bozzo et al. 2013, 2018).

Although these sources are formally part of the LMXBs class due to the low mass of the red giant donor star, their behaviour in the X-ray domain strongly resembles that of the high mass X-ray binaries (HMXBs). SyXBs show long pulse periods, ranging from hundred of seconds to hours, and display a high pulsed fraction that can be as large as 30-50%. They are characterized by the longest orbital periods among the known LMXBs (several tens to thousand days) and a prominent variability in the X-ray domain by a factor of ~10-20 typical of wind-fed HMXBs. These properties strongly suggest the presence of a highly magnetized NS (at least >10¹² G) in the SyXBs.

The evolutionary calculations available so far (Postnov et al. 2010; Lü et al. 2012; Kuranov & Postnov 2015) assume a priori that the progenitor of a SyXB is a binary system initially hosting a strongly magnetized NS and a low mass main sequence star (~M⊙) in a wide orbit (hundreds of days). In the early stages of evolution, the secondary star is on the first giant branch but does not fill its Roche lobe, leading to a negligible mass transfer toward the NS and thus to negligible high-energy emission. When this is no longer the case, as the magnetic field of the NS is assumed not to have decayed and its rotational velocity is still high, the system enters in a so-called “propeller” phase. Inflowing material from the donor star is ejected from the vicinity of the NS and accretion is still largely inhibited. This occurs at the expense of the rotational energy, inducing a rapid increase of the NS spin period up to ≳10000 s (Bozzo et al. 2008; Shakura et al. 2012). As little to no accretion is taking place in this stage, the system is hardly detectable in the X-ray domain. The situation changes when the NS has slowed down sufficiently to reduce the centrifugal force at the magnetospheric boundary and allows some accretion to take place, finally shining as a SyXB. In this phase, accretion is still likely to take place directly from the stellar wind. As this is endowed with little to no angular momentum, the spin period of the NS is still expected to increase because of the effect of the friction between the relatively large magnetosphere and the surrounding dense environment. In the following evolutionary phase, the velocity of the stellar wind decreases to a level at which the formation of an accretion disk around the compact object is inevitable (Wang 1981). Accretion in this phase leads to rapid decrease

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1 We take into account here the fact that 3A 1954+319 has been recently reclassified as a classical supergiant X-ray binary (Hinkle et al. 2020; Bozzo et al. 2022).
of the NS spin period and the system finally resembles a common LMXB with a fast spinning compact object (see Fig. 1 of Lü et al. 2012).

One of the most puzzling aspects of SyXBs concerns the presence of a strongly magnetized NS in a system that has to be at least several Gyr old to allow the donor star to evolve to the red giant phase. The measurement of the NS magnetic field is usually obtained through the detection of cyclotron resonant scattering features (CRSFs). These are absorption features in the X-ray spectra of NS binaries that were first discovered in Her X-1 (Trümper et al. 1977; Trümper et al. 1978) and later identified in several other systems (Heindl et al. 2004; Schönherr et al. 2007). Long-standing theoretical developments have shown that the NS magnetic field should decay with time especially in the presence of accretion, and this is the main reason why the bulk of the LMXBs host weakly magnetized NSs (Tauris 2015). An alternative possibility put forward is that the NS formed much later in the evolution of the SyXB due to the accretion induced collapse of a white dwarf accreting from the stellar wind of the red giant. The white dwarf would have an age compatible with that of the red giant companion, while the NS forms more recently after a long phase of accretion. This allows the NS to preserve its high magnetic field up to the point in time at which the system shines as a SyXB. So far, the accretion induced collapse of a white dwarf remains a relatively poorly known process and it is a matter of debate if a strongly magnetized NS (at the level of $10^{12}$ G) can be produced by conservation of a sufficiently intense white dwarf magnetic flux during the collapse (see, e.g., Tauris 2015, and references therein).

Only in the case of the SyXB IGR J17329−2731 the presence of a strongly magnetized NS could be firmly established thanks to the detection of a CRSF at $\sim 21$ keV, providing an estimate of the compact magnetic field strength as high as $2.4 \times 10^{12}$ G (Bozzo et al. 2018). This discovery called for further observations of IGR J17329−2731, as well as of other SyXBs, to consolidate our understanding on the formation channels of these systems.

In this paper, we pursue the search for CRSFs in SyXBs through the broad-band spectral analysis of the X-ray emission from two known sources in this class, Sct X−1 and 4U 1700+24. For the first source, we report on our simultaneous observation with Chandra and NuSTAR. For 4U 1700+24, we exploit a public but yet unpublished NuSTAR observation, as well as previously performed broad-band observations with the XRT and BAT on-board Swift during three outbursts of the source that occurred in 2014 and 2015. We additionally report in this paper on the outcomes of our long-term observational campaign with Swift/XRT on the most recently discovered SyXB IGR J17329−2731, covering up to nine months after its first detection in the X-rays (August 2017).

2 Sct X−1

Sct X−1 was discovered in 1974 (Hill et al. 1974) and subsequently observed with a variety of X-ray facilities. The system is known to host a 111 s spinning NS and is characterized by a remarkably high local absorption column density reaching up to $\sim 10^{23}$ cm$^{-2}$. It also showed a prominent variability (from 0.3 to 20 mCrab, corresponding to $5 \times 10^{-12}$ to $3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) on a large range of timescales and the presence of a neutral iron line emission that was detected in its X-ray spectrum already back in the ‘90s (the HEAO 1 satellite detected Sct X−1 up to $\sim$100 keV; see Koyama et al. 1991a, and references therein). The best determined source position to date was obtained through an XMM-Newton observation reported by Kaplan et al. (2007). These authors could use the improved source localization (1 arcsec) to identify the optical counter-part of the X-ray source and proposed that the NS in Sct X−1 is coupled to a late type giant about 4 kpc away from us. This led to the classification of Sct X−1 as a SyXB in our Galaxy. The XMM-Newton data revealed also that the source had continuously spun down from the late ‘90s to 2004, and the best measured pulse period from XMM-Newton was 112.86±0.08 s. Kaplan et al. (2007) further found that since the late ‘90s the source had decreased in flux substantially, reaching at the time of the XMM-Newton observation a flux of 0.4 Crab (corresponding to $1.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5−10 keV energy band). The spectrum measured by the EPIC cameras on-board XMM-Newton proved to be significantly harder compared to previous measures with HEAO 1 and Ginga (the power-law photon index decreased from $\sim$2.0 to $\sim$1.5), and the absorption column density was shown to have decreased by a factor of few (from $2−4 \times 10^{23}$ cm$^{-2}$ to $8 \times 10^{22}$ cm$^{-2}$; see Cooke et al. 1984; Koyama et al. 1991b). No additional X-ray observations were performed toward Sct X−1 between 2004 and 2014. More recently, De et al. (2022) reported on the first broad-band IR spectroscopic investigation of the source and re-classified the companion as a M8−9 III type O-rich Mira donor star, rather than a red giant. This makes Sct X−1 a peculiar member of the SyXBs and the first known NS binary with a Mira companion.

In this paper, we report on an observational campaign aimed at Sct X−1 (almost) simultaneously with Chandra and NuSTAR. We also exploit two yet unpublished archival Suzaku observations pointed at the source.

Sct X−1 was observed with Chandra on 2020 November 9 at 01:50 (UT) for a total exposure time of 28.7 ks (PI: E. Bozzo). The observation was carried out with the ACIS-S in Faint mode (timed exposure). We processed the Chandra data with standard techniques using CIAO v4.3 and the latest CALDB available at the time of writing (v.0460; released on 2021 September 23). Only one source was detected in the ACIS image extracted in the 0.5−10 keV and the best determined position using the CIAO (v4.3) tool celldetect is at RA=$278.85755$ and DEC=$−7.61408$ with an associated uncertainty at 90% c.l. of 0.6 arcsec. This position is fully consistent with that previously reported by Kaplan et al. (2007); De et al. (2022) and within 0.3 arcsec from the selected counterpart of Sct X−1 (2MASS J18352582−0736501). This confirms the classification of Sct X−1 with the Galactic SyXB.

Using the CIAO tool dmextract, we determined that only about 170 effective counts were recorded from the source and thus we did not attempt any timing investigation, limiting the analysis to the sole extraction of a time-averaged spectrum (rebinned to have at least 25 counts per energy bin). The corrected source spectrum was extracted using the CIAO tool specextract and could be well fit ($\chi^2$/d.o.f.$\approx 6.1/7$) with a simple absorbed powerlaw model (tbabs*powerlaw in Xspec). We adopted the wilms abundances (Wilms et al. 2000) and ver9 cross sections (Verner et al. 1996). We measured an absorption column density of $N_H=(5.0^{+2.5}_{−1.0}) \times 10^{22}$ cm$^{-2}$ and a photon index of $\Gamma = 1.8^{+0.7}_{−0.5}$. The estimated 0.5−10 keV X-ray flux was $2.1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. These results are fully consistent with those reported by De et al. (2022).

NuSTAR observed Sct X−1 starting on 2020 November 8 at 18:16 for a total exposure time of 32.5 ks (PI: E. Bozzo). We reduced the data-set using standard techniques and the caldb version re-

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2 See https://cxc.cfa.harvard.edu/ciao/threads.
3 See https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf
leased in 2021 December 2. We first extracted both the FPMA and FPMB images and noted that a single faint source was detected at a location compatible with the Chandra position of Sct X−1 reported above. Given the faintness of the source (about 320 counts were collected by both the FPMs), it was not possible to carry out a study of the source lightcurve or perform any timing analysis. We thus extracted only the time averaged spectra (rebinned to have at least 25 counts per energy bin) and fit the data from both FPMs together. The source spectrum could be well described by an absorbed powerlaw model ($\chi^2$/d.o.f. = 9.0/13). We measured $N_H$=$(1.4 \pm 0.8 \times 10^{22})$ cm$^{-2}$ and $\Gamma = 3.8_{-0.6}^{+1.0}$. The estimated $3−20$ keV X-ray flux was $2.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. A normalization constant was included in the fit to take into account cross-calibrations between the FPMA and FPMB but it turned out to be fully compatible with unity.

We also fit simultaneously the Chandra and NuSTAR data. In this case, we obtained $N_H=$(8.6$^{+3.0}_{-2.6}$) $\times 10^{22}$ cm$^{-2}$ and $\Gamma = 2.9_{-0.5}^{+0.6}$ ($\chi^2$/d.o.f. = 17.7/22). The normalization constant introduced to take into account cross-calibrations between Chandra and NuSTAR was measured at 0.6$\pm$0.2 (fixing the NuSTAR constant to unity for reference). We show the results of the fit to the broad-band spectrum of Sct X−1 in Fig. 1.

We noted that two Suzaku observations of Sct X−1 were also carried out in 2014 October 10 at 12:43 and in 2014 October 22 at 02:45 (UT). The exposure time available for the XIS instrument was of 15.2 ks and 38.6 ks, respectively. We obtained from the HEASARC archive the pre-processed XIS data and verified that no source was detected at a position consistent with Sct X−1. We adopted the ximage tool and the command upload available within HEASOFT v.6.29c to estimate an upper limit on the source X-ray flux (see Bozzo et al. 2012, and references therein). From the shorter observation, we obtained a $3\sigma$ upper limit on the source count-rate of 0.22 cts s$^{-1}$, while the longer observation returned an upper limit of 0.15 cts s$^{-1}$. By using the online tool w3pimms and the spectral model measured from the Chandra + NuSTAR data, we converted the above values into a $3\sigma$ upper limit on the source 0.5−10 keV X-ray flux of $8.6 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ and $5.6 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, respectively.

![Figure 1. Broad-band (unfolded) X-ray spectrum of Sct X−1 combining the Chandra ACIS-S (green) with the NuSTAR FPMA (black) and FPMB (red) data. The best fit is obtained with a model comprising an absorbed powerlaw. The residuals from the fit are shown in the bottom panel.](https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl)

4 https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl

### 3 4U 1700+24

4U 1700+24 was discovered in the ‘70s and it is known since then to be a relatively bright persistent X-ray source (see, e.g., Garcia et al. 1983; Nucita et al. 2014; Hinkle et al. 2019, and references therein). The source is known to host an accreting NS which pulsations have been so far elusive most likely due to the pole-on direction through which the system is being observed. The source shows a remarkable variability in X-rays, achieving a total dynamic range of at least ~200, considering also that the source has been detected undergoing short outbursts a few times by both Swift and MAXI (Kennel et al. 2014; Fukushima et al. 2014; Burrows et al. 2014, 2015). The M giant companion is relatively well studied and it has been recently reported though long-term optical and near-IR observations the discovery of its pulsating period (about 420 days), as well as the orbital period of the system measured at ~12.0 years (Hinkle et al. 2019). This is by far the longest known orbital period for a SyXB and the detailed modeling of the optical data provided support in favor of the previous finding that the system is observed pole-on, with an estimated orbital inclination of 11.3$\pm$0.4$.^4$ The measurement of the distance to the source has been also recently improved thanks to the Gaia data at 0.536$\pm$0.009 kpc (Armstrong et al. 2021).

In the soft X-ray domain (≤10 keV), the spectral energy distribution of the source is usually described by using a model comprising a thermal black-body emission dominating below ~2 keV and a comptonization component (see, e.g., Nucita et al. 2014, and references therein). A red-shifted O VIII Ly-$\alpha$ transition line has been detected multiple times by using the RGSs on-board XMM-Newton and so far ascribed to either the re-organization of the X-ray emitting material close to the NS magnetic poles or to the presence of a unipolar jet of matter emitted by the NS with velocities of the order of few 1000 km s$^{-1}$. A study of the broad-band X-ray emission from 4U 1700+24 was carried out in the past by Masetti et al. (2002) using a combination of ROSAT, ASCA, RXTE, and BeppoSAX data, as well as by Nagae et al. (2008) using Suzaku data. No evidence of a cyclotron line was found, with the broad-band spectra of the source being well described by the same combination of components mentioned above.

In this paper, we report on a yet unpublished NuSTAR observation of 4U 1700+24 carried out from 2014 October 2 at 10:26 (UT) to October 3 at 15:21 for a net exposure time of 51.6 ks over 102 ks of observation. We made use of data from both the FPMA and FPMB in the energy range 3−79 keV, processing the data with the nupipeline (version 0.4.9) available within the HEASOFT (version 6.29) and the version 20211020 of the calibration database. The processing provided us the cleaned event files. We used extraction regions of two arcminutes radius for both source and background products. These region files were used as input to nuproducts (version 0.3.3) to obtain the source and background lightcurves and spectra. We verified that different reasonable choices of the location of the background region and of the radius of extraction do not affect our results.

The source lightcurve was extracted with bins of one second and adaptively rebinned to reach a signal to noise ratio of at least 25 in each bin (see Bozzo et al. 2013, for details on the adaptive hardness ratio rebinning employed in several of our papers). As it can be appreciated in Fig. 2, the source lightcurve shows a moderate variability that is not accompanied by significant changes in the spectral properties (the hardness ratio, HR, remained virtually constant across the entire observation). This was confirmed by the usage of a Bayesian block analysis (the same exploited in a number of our previous papers; see, e.g., Ferrigno et al. 2020) which thus convinced...
us to extract a single spectrum using the entire exposure time available to investigate the properties of the broad-band X-ray emission from 4U 1700+24.

The spectrum in the 3–70 keV range was rebinned using the optimal grouping method described by Kaanstra & Bleeker (2016) and the Cash statistics (C-stat in Xspec) was adopted to evaluate the goodness of all fits. We first tested a simple phenomenological model to describe the source spectrum, comprising a cutoff power-law component ((highecut*pegpwrlw) in xspec) attenuated by neutral absorption at the lower energies (TBabs in xspec). We adopted for the absorption component Verner cross sections (Verner & Yakovlev 1995) and “Wilm” abundances (Wilms et al. 2000). The best-fit parameters were determined using the modified Levenberg-Marquardt algorithm based on the CURFIT routine from Bevington, while uncertainties on the parameters were obtained by running a Monte Carlo Markov Chain (MCMC) with the Goodman-Weare sampling algorithm. We used 60 walkers, a burn-out of 6000 steps, and a chain length of 36 000. Priors were uniform for the slope and uniform in logarithmic scale for all other parameters. We set parameter limits wide enough not to influence the posteriors. To assess the goodness of the fit, we sampled 1 000 parameter sets derived from the MCMC, simulated a spectrum based on that model with the same exposure and background of the measured one, and performed a fit. We compared the C-stat of the simulated set to the one derived from the data and found that all simulations yield a better fit statistic. We thus concluded that the model had a probability less than 0.1% to be statistically acceptable.

Driven by the visual inspection of the residuals from the above fit, we tested the improvement of the results by adding to the simple phenomenological model either a black-body or two broad Gaussian absorption lines with centroid energies fixed to be one the double of the other. These two more complete models gave equivalently acceptable results. The black-body radius turned out in the fit to have a radius compatible with that of an hot spot on the NS surface, providing a 17% contribution to the total 1–10 keV unabsorbed flux. In the model featuring absorption Gaussian lines, the width of the fundamental feature is of 8 or 5 keV depending if we include or not the first harmonic in the fit. The latter turned out to be only marginally significant, but the different panels reported in Fig. 3 shows how the introduction of this second feature is able to treat the otherwise evident residuals around 30 keV. All results of the above fits are summarized in Table 3. For completeness, we also tested alternative models for the description of the source continuum emission that are commonly exploited in case of strongly magnetized accreting NSs, as the Fermi-Dirac cutoff or the NPEX. None of these provide significant improvements over the phenomenological model and thus are not further discussed.

The Swift/BAT Transient Monitor (Krimm et al. 2013) shows that 4U 1700+24 was very active during 2014 and early 2015. Indeed, it triggered the BAT three times within four months. In this paper, we exploit the quasi-simultaneous BAT and XRT data collected during these triggers (see the complete log in Table 2) in order to perform an additional broad-band spectral analysis of the source beside that made possible by the previously reported NuSTAR data. The Swift data of 4U 1700+24 were uniformly processed and analysed using the standard software (FTOOLS6 v6.29b), calibr-
to the data and response matrices were created with CALDB\textsuperscript{7} using the latest spectral redistribution matrices. The Swift/XRT data were filtered with the task\texttt{xrtpipeline} (v0.13.6). Data below 1 keV were discarded in order to avoid known instrumental residuals affecting the WT mode\textsuperscript{8}. In the following, we analyse the observations corresponding to the different BAT triggers (ObsID 00612974000, 00621278000, and 00623434000), each consisting of three orbits of data. For each trigger, we selected a quasi-simultaneous pair of XRT and BAT spectra. Fits to each pair of spectra were performed using the same models discussed before for the NuSTAR data and including a constant to take into account both the difference of exposure and the non strict simultaneity of the XRT and BAT data.

4U 1700+24 triggered the BAT for the first time on 2014 September 17 at 13:30:35.5 UT (image trigger 612974, $T_0 = \text{MJD } 56917.56291043$; Burrows et al. 2014); Swift immediately slewed the target so that the narrow field instruments (NFI) started observing the source at $T_0 + 1183$ s (see Table 2). During the observation ObsID 00612974000, the source was significantly detected in the BAT up to $\sim 70$ keV and the BAT lightcurve shows only a moderate variability. We checked that, when fit with a simple power-law, the first orbit spectrum and the bright spectrum ($T_0 + 524–733$ s) feature consistent parameters despite a difference by factor of two in flux. In the XRT, the source showed significant flux variability not corresponding to comparable variability in its spectral properties (as also noted by Burrows et al. 2014). The pile-up corrected count rate is seen to vary from a maximum of $\sim 70$ c s\textsuperscript{-1} to a minimum of $\sim 2$ c s\textsuperscript{-1} but the hardness ratio calculated in the 0.3–4 keV and 4–10 keV energy bands does not show significant variations. XRT data collected in the first and third orbit comprised only a few seconds of exposure, with the bulk of the photons collected during the second orbit. To maximize the signal-to-noise ratio, we thus considered for our broad-band spectral analysis only the quasi-simultaneous BAT bright spectrum ($T_0 + 524–733$ s) and the XRT/WT spectrum from the second orbit ($T_0 + 5634–6188$ s). A fit to these data using an absorbed power-law with an exponential cutoff (TBabs*highecut*pegpwrlw) provided satisfactory results. We report in Table 2 the best-fit spectral parameters and the total $\chi^2$ test statistics. By inspecting the residuals from the fit (see Fig. 4), we found no evidence for the presence of a black-body component. Due to the lack of energy coverage in the range 10-15 keV and the limited statistics of the BAT data around 30 keV, we could not evaluate the presence of the possible absorption features revealed by the fit to the NuSTAR data (see earlier in this section). We note, however, that the addition of two Gaussian absorption components with parameters fixed to those determined by NuSTAR did not cause a worsening of the fit and could thus be compatible with the XRT+BAT data.

The second outburst of the source occurred on 2014 December 13 at 01:56:11.09 UT (image trigger 621278, $T_0 = \text{MJD } 57004.08068392$; Kennea et al. 2014) and caused an immediate slew, so that the NFIs were on target at $T_0 + 120$ s. The properties of the Swift data of the first observation (ObsID 00612178000) are strikingly similar to those observed in the first trigger, with a remarkable X-ray variability and dynamic range (minimum to maximum $\sim 5–10$ c s\textsuperscript{-1}) associated with a substantially constant hardness ratio. Similarly to what was done for the first trigger, we only consider for our analysis the quasi-simultaneous BAT first orbit spectrum ($T_0 - 239$ s to $T_0 + 693$ s) and the XRT/WT first orbit spectrum ($T_0 + 120–1561$ s). The spectra were fit as was done above for the first trigger and we found compatible results (see Table 2). The same

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\textsuperscript{7} https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb\_intro.html.

\textsuperscript{8} We adopt the $T_{\text{total}}$ baseline, that is the time over which all fluence is emitted, as calculated by barmx.

\textsuperscript{9} https://www.swift.ac.uk/analysis/xrt/digest\_cal.php.
conclusion concerning the presence of the black-body and the Gabs absorption components applies.

The third outburst of the source occurred a few days later on 2015 January 4 at 15:39:06.99 UT (image trigger 623434, T0 = MJD 57026.65216427; Burrows et al. 2015) and caused an immediate slew, so that the NFIIs were on target at T0+406 s. The Swift data of the first observation (ObsID 00623434000) also show the X-ray variability and dynamic range (minimum to maximum ∼ 5–130 c s⁻¹) associated by a substantially constant hardness ratio. We only consider for our analysis the quasi-simultaneous BAT bright spectrum (T0 + 0–320 s) and the XRT/WT first orbit spectrum (T0 + 406–1818 s). The spectra were fit as was done above for the previous triggers, obtaining similar results and the same conclusions concerning additional spectral components beside the absorbed cut-off power-law (see Table 2). As both the combined XRT+BAT spectra of the second and third trigger were relatively similar to those of the first trigger, we did not show for brevity the corresponding images of the best fit models and residuals from the fits.

4 IGR J17329–2731

IGR J17329–2731 was discovered by INTEGRAL in 2017 (Postel et al. 2017) and rapidly pointed at a number of different facilities giving rise to a prompt multi-wavelength campaign. Observations carried out with XMM-Newton and NuSTAR revealed the presence of prominent pulsations at a period of 6680 s and of a CRSF with a centroid energy of ∼20 keV. These findings confirmed the presence of a NS accretor in this system endowed with a magnetic field of 2.4×10¹²(1 + z) G, with z gravitation redshift at the NS surface. The positional accuracy provided by Swift/XRT allowed also for the identification of the optical counterpart through SOAR observations as a late M giant at a distance of 2.7±1.2 kpc. IGR J17329–2731 was thus classified as a new member of the SyXBs (Bozzo et al. 2018; Bahramian et al. 2017). Although no pointed observation with sensitive X-ray telescopes was available before the discovery in 2017, Bozzo et al. (2018) used the entire available INTEGRAL archive to show that the source was likely never detectable before in the high energy domain and thus the observations carried out in 2017 might have as well discovered the very first moment when the source shone as a SyXB.

Following the discovery of the source, a long-term monitoring campaign was initiated with Swift/XRT in order to investigate the evolution of this object in the X-ray domain. In this paper, we report on the results of this concluded campaign. The Swift data of IGR J17329–2731 were uniformly processed and analysed using the standard software (FTOOLS10 v6.29b), calibration (CALDB11 20210915), and methods. The Swift/XRT data were filtered with the task xrtpipeline (v0.13.6). A log of all available XRT observations of IGR J17329–2731 is reported in Table 1.

We first extracted the source average count-rate for each observation in two energy bands, 0.5–4 keV and 4–10 keV, to compute the hardness-ratio (HR) reported also in Table 1. We then extracted for each observation the average spectrum of the source and fit it with a simple absorbed power-law model (the same as used in Sect. 2). We note that the XRT observations of IGR J17329–2731 are generally composed by 1 up to 3 snapshots with typical exposures of 300–1000 s. Therefore, none of the XRT observations is suitable to look for pulsations; furthermore the energy dependence of the pulse profile is unlikely to bias the HR value computed for each observation. The results of these analysis are summarized in Fig. 5.

The energy spectral distribution of the source in the XRT energy band is generally well described by simple absorbed power-law model, but there are intervals of time where the fits to the spectra with such simple model leave evident residuals around the typical energy of the neutral iron line at ~6.4 keV. During these intervals, the source is relatively faint and achieves a flux that is a factor of 5–10 lower than the surrounding time intervals. We also observe simultaneously during these intervals a flattening of the spectrum and a drop by a factor of few in the absorption column density, thus resembling what we usually observe in wind-fed systems during X-ray eclipses or obscuration events (see, e.g., Bozzo et al. 2009, and references therein). Although all spectral results are reported in Table 1, we also show a plot of the parameters as a function of time in Fig. 5 to ease the visual inspection. As it can be appreciated for this figure, the intervals corresponding to the obscuration events are concentrated during the second observational period (58150–58396 MJD) and occur in the time intervals separating the different source flares observed (4 flares are apparent in total during this period). The time interval characterized by the iron line with the largest equivalent width (≥2 keV) is centered around ~58240 MJD and it is also featuring the lowest recorded flux as well as one of the softest measured X-ray spectra. To illustrate the dramatic change in the source spectral properties between the emission during and outside the obscuration events, we show a comparison of typical spectra for the two cases in Fig. 6.

Although the uncertainties associated with the measurements of the iron line centroid energies in the different obscuration intervals in Table 1 is relatively large, we see also from Fig. 6 a marginal evidence for a change of the centroid between 6.4 keV up to 6.7 keV. In order to improve the measurements of the iron line, we thus stacked together all data collected during the obscuration intervals and obtained the spectrum that we show in Fig. 7. As expected based on the findings above, the spectrum appears relatively flat, and there is a prominent feature around 6.4 keV emerging from the residuals if the spectrum is fit with a simple absorbed powerlaw (in this case the result would be largely unacceptable with χ²/d.o.f. = 147.5/45).
Table 2. Swift/XRT observation log of 4U 1700+24: observing sequence, date (MJD of the start of the observation), start and end times (UTC), XRT exposure time, and time since each BAT trigger for the start of the observation. We also indicated for each BAT+XRT spectral pair the value of the intercalibration constant, the absorption column density $N_H$, the powerlaw photon index $\Gamma$, and the flux in the 1–10 keV energy band (not corrected for absorption) determined from the spectral fit, as well as the values of the cutoff energy ($E_C$) and e-folding energy ($E_F$) of the (highcut) model.

| Sequence | MID     | Start time (UTC) (yyyy-mm-dd hh:mm:ss) | End time (UTC) (yyyy-mm-dd hh:mm:ss) | Exposure (s) | Time since trigger (s) | $C_2$ | $N_H$ 10$^{22}$ cm$^{-2}$ | $\Gamma$ | $F_{1-10}$ keV 10$^{-11}$ | $E_C$ keV | $E_F$ keV | $\chi^2$/d.o.f. |
|----------|---------|----------------------------------------|--------------------------------------|--------------|------------------------|-------|-------------------------|----------|-------------------------|----------|----------|------------------|
| 00612974000 BAT | 56917.56128 | 2014-09-17 13:28:15 | 2014-09-17 13:46:48 | 1113 | -150 | 2.64$^{+0.84}_{-0.76}$ | 0.37$^{+0.12}_{-0.14}$ | 0.93$^{+0.12}_{-0.19}$ | 79.6$^{+0.08}_{-0.08}$ | 4.5$^{+1.4}_{-2.1}$ | 19.6$^{+7.5}_{-4.94}$ | 208.72/203 |
| 00612974000 WT | 56917.57672 | 2014-09-17 13:30:28 | 2014-09-17 16:38:20 | 629 | 1183 | 1.40$^{+0.81}_{-0.52}$ | 0.30$^{+0.07}_{-0.05}$ | 0.79$^{+0.08}_{-0.09}$ | 108.8$^{+4.1}_{-2.3}$ | 5.0$^{+0.6}_{-0.5}$ | 7.0$^{+1.3}_{-1.0}$ | 501.32/471 |
| 00621278000 BAT | 57004.07803 | 2014-12-13 01:52:22 | 2014-12-13 05:37:37 | 13516 | -239 | 1.27$^{+0.43}_{-0.53}$ | 0.23$^{+0.06}_{-0.06}$ | 0.71$^{+0.05}_{-0.05}$ | 210.6$^{+11.2}_{-9.2}$ | 3.87$^{+0.57}_{-0.52}$ | 11.3$^{+2.8}_{-2.0}$ | 574.87/586 |
| 00621278000 WT | 57004.08219 | 2014-12-13 01:58:20 | 2014-12-13 06:38:33 | 2002 | 120 | 1.27$^{+0.43}_{-0.53}$ | 0.23$^{+0.06}_{-0.06}$ | 0.71$^{+0.05}_{-0.05}$ | 210.6$^{+11.2}_{-9.2}$ | 3.87$^{+0.57}_{-0.52}$ | 11.3$^{+2.8}_{-2.0}$ | 574.87/586 |
| 00623434000 BAT | 57026.64951 | 2015-01-04 15:35:18 | 2015-01-04 19:12:02 | 13195 | -239 | 1.27$^{+0.43}_{-0.53}$ | 0.23$^{+0.06}_{-0.06}$ | 0.71$^{+0.05}_{-0.05}$ | 210.6$^{+11.2}_{-9.2}$ | 3.87$^{+0.57}_{-0.52}$ | 11.3$^{+2.8}_{-2.0}$ | 574.87/586 |
| 00623434000 WT | 57026.65698 | 2015-01-04 15:46:02 | 2015-01-04 19:01:06 | 4656 | 406 | 1.27$^{+0.43}_{-0.53}$ | 0.23$^{+0.06}_{-0.06}$ | 0.71$^{+0.05}_{-0.05}$ | 210.6$^{+11.2}_{-9.2}$ | 3.87$^{+0.57}_{-0.52}$ | 11.3$^{+2.8}_{-2.0}$ | 574.87/586 |

Figure 5. Plot of the energy resolved count-rate (soft is in 0.5–4 keV, while hard is 4–10 keV), HR, absorption column density, power-law photon index, flux, iron line centroid energy and equivalent width as a function of time obtained from the fut to the XRT data of IGR J17329–2731. Each point in the plot corresponds to one observation in the Table 1, unless observations have been stacked together as in the table to obtain a sufficient signal-to-noise ratio.

Adding a single thin Gaussian component (width fixed to zero) improves the fit ($\chi^2$/d.o.f.=73.9/43) but leaves significant residuals in the energy range 6.7–7.0 keV. Adding a second Gaussian component centered at 6.7 keV further improves the fit down to $\chi^2$/d.o.f.=49.2/41. From this fit, we measured an absorption column density of $N_H=(2.8^{+1.9}_{-1.0})\times10^{22}$ cm$^{-2}$, a powerlaw photon index of $\Gamma=-0.8\pm0.2$, and a 0.5–10 keV flux of $1.2\times10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (not corrected for absorption). The measured centroid energies of the two iron lines in this case are 6.41±0.06 keV and 6.8±0.1 keV. The corresponding equivalent widths (EQWs) were $0.83^{+0.17}_{-0.40}$ keV and $0.48^{+0.12}_{-0.30}$ keV, respectively. Although the fit is formally acceptable, we still noticed residuals around 7 keV. We thus attempted to add a third Gaussian line and obtained a centroid energy for this line of 6.9±0.1 keV while all other parameters remained unchanged to within the uncertainties. The improvement of the fit with the third line is not statistically significant ($\chi^2$/d.o.f.=39.6/39), but it is interesting to note that the three lines correspond to the known predominant states of iron typically observed in wind-fed HMXBs (neutron stars).
iron line at 6.4 keV, He-like iron line at 6.7 keV, and H-like iron line at 6.9 keV; see, e.g., Fürst et al. 2011; Liu et al. 2018, and references therein). For completeness, we mention that the residuals around the iron line complex could also be alternatively fit (with a single large Gaussian component (leaving the continuum parameters virtually unchanged). In this case, the centroid energy would be 6.52±0.06 keV and the line width 0.27±0.07 keV. We consider this fit unphysical as the centroid energy of the line would only be marginally compatible with the neutral iron value and a broadening of the line would only be expected in case of a fast rotating accretion disk around a weakly magnetized NS (see, e.g., Di Salvo & Sanna 2020, for a recent review) but not in a wind-fed
young pulsar as that hosted in IGR J17329−7371 (see the discussion in Torrejón et al. 2010).

5 DISCUSSION

We reported in this paper about the broad-band X-ray spectroscopy of two of the few known SyXBs, Sct X−1, and 4U 1700+24. We have been looking specifically for the presence of CRSFs in their spectral energy distribution that could point toward the presence
of strongly magnetized NSs in these systems and support the idea that they can be formed through the accretion induced collapse of a white dwarfs (a yet relatively poorly known NS formation channel, see Sect. 1). Furthermore, we reported on our long-term monitoring campaign on the latest discovered SyXB, IGR J17329–2731, carried out with the Swift/XRT up to nine months following the first detection of the source in the X-ray domain.

In the case of Sct X–1, we exploited our simultaneous Chandra and NuSTAR observation performed in 2020. The source turned out to be relatively faint, with an average flux that decreased about two orders of magnitude compared to the previous X-ray observations carried out in 2004 with XMM-Newton. The slowly decreasing trend in the source flux is confirmed also by two Suzaku observations performed in 2014 where the source was not detected (the upper limit we provided is a factor of few higher than the flux values determined by both Chandra and NuSTAR). Although the statistics of the combined Chandra and NuSTAR data was relatively poor, we could shows that the source dimming over the past decades is accompa-
absorption column density constantly in excess of $10^{23}$ cm$^{-2}$) was already reported for the other (yet poorly known) SyXB XTE J1743-363 (Smith et al. 2012; Bozzo et al. 2013).

For 4U 1700+24, we looked for the possible presence of CRSFs in the X-ray spectral energy distribution of the source by exploiting a public (but not yet published) NuSTAR observation of the source, as well as simultaneous XRT+BAT spectra collected during three outbursts of the source caught by Swift in 2014 and 2015. When the broad-band spectrum obtained from both the FPMA and FPMB onboard NuSTAR is fit with a simple cut-off power-law model, significant residuals are found especially around 15 keV. These residuals suggested the presence of a broad absorption feature, similarly to what is usually expected for a CRSF. Interestingly, the FPMA and FPMB spectra also showed some marginal evidence for the first harmonic of this feature due to additional residuals around 30 keV. If our interpretation is correct, the NS hosted in 4U 1700+24 could be endowed with a magnetic field strength of $\sim 1.4 \times 10^{12}$ G (see, e.g. Staubert et al. 2019, for the conversion of the CRSF centroid energy line into the NS magnetic field strength). This is the first claim of a CRSFs in the X-ray spectrum of 4U 1700+24. We note that past investigations on the X-ray broad-band spectral energy distribution of the source were carried out (to the best of our knowledge) only by Masetti et al. (2002) and Nagae et al. (2008). These authors exploited mainly BeppoSAX, and Suzaku data where the energy range 10-30 keV is poorly covered (or missing) due to the limited overlap of the operational energies of the available instruments. Masetti et al. (2002) also reported on a RXTE/PCA spectrum of the source extending continuously from 3 to 20 keV. Also in this case, no CRSF was reported. We remark, however, that the fundamental line identified in our NuSTAR spectra would sit right at the rim of the PCA energy coverage of that spectrum and thus might have easily gone undetected in the fit. There is also the possibility that the CRSF was not visible during the PCA observation, as we known that CRSF might be dependent on the viewing direction of the observer compared to the magnetic field orientation and could change along the pulse period or at different luminosity levels (impacting, e.g., the shape of the accretion column where the CRSFs are most likely originating; see, e.g., Kretschmar et al. 2019, and references therein).

However, it must be remarked that the present statistics of the NuSTAR data does not allow us to firmly exclude alternative models to describe the broad-band spectral energy distribution of 4U 1700+24. The FPM spectra could be equivalently well described using the addition of a black-body component to the cut-off power-law in place of the two absorption features. The presence of a similar thermal component would not be unexpected, as it was previously reported for this source by Nucita et al. (2014) while analyzing XMM-Newton and SwiftXRT data outside the outbursts. If we compare the results from these authors with those in Table 3, we note that the black-body component required by the NuSTAR data is significantly hotter ($1.4$ keV vs. the previously reported 0.7-1.0 keV) and would be dominating a large portion of the XRT energy coverage. Curiously enough, the broad-band XRT+BAT spectra that we obtained by analyzing the source behavior during three different outbursts did not show the presence of any thermal component. Although the energy coverage and statistics of all XRT+BAT data did not allow us to investigate in details the presence of the CRSF at $\sim 16$ keV and its harmonic, we discussed in Sect. 3 that the broad-band fits would be compatible with the (undetected) presence of these features, if their parameters are frozen to those measured by NuSTAR.

We thus conclude that at present it is not possible to firmly confirm the moderate softening of the spectrum (the power-law photon index increased from $\sim 1.5$ in 2004 to roughly $\sim 3.0$ in 2020), No evidence of CRSF was found in the broad-band spectrum of the source. The slow decade-long dimming and softening of the source emission is not easy to interpret in the context of wind-fed SyXBs, but it is worth noticing that such behavior (accompanied by a local
or reject the presence of CRSFs in the broad-band X-ray spectrum of 4U 1700+24. Deeper observations of this system with NuSTAR, featuring the uniquely required combination of sensitivity and large energy coverage, are needed to understand if 4U 1700+24 is the second SyXB to host a strongly magnetized NS and evaluate further the impact of these results for the formation channels of extreme compact objects from accreting aged white dwarfs.

IGR J17329−2731 was the first SyXB with a detected CRSF, leading to the identification in this system of a young NS endowed with a magnetic field strength of \( \sim 2 \times 10^{12} \) G (see Sect. 1). The observations collected during our long-term XRT monitoring showed that the source never turned off as an X-ray emitter after its initial detection and remained active at a virtually constant average flux level of few times \( 10^{-11} \) erg s\(^{-1}\) cm\(^{-2}\). It also underwent sporadic flares lasting a few days at the most and achieving a total dynamic range in the X-ray flux of about \( \sim 30 \) (see Fig. 5 and Table 1).

On one hand, the findings of the monitoring program corroborated the idea proposed by Bozzo et al. (2018) that IGR J17329−2731 turned on in 2017 for the first time as a SyXB, beginning effectively to be a variable but persistent source as all other objects in this class. On the other hand, the reason for the onset of such X-ray activity remains unclear. Bozzo et al. (2018) proposed that the red giant might have gone through some thermal pulse phase that had enhanced the mass loss rate toward the NS and so triggered a sufficiently intense accretion to be detectable for the first time in X-rays (explaining also the brightening of the optical star in the R-band). We can investigate here a slightly different possibility.

The flares and in general the prominent X-ray variability of the source revealed by our monitoring is commonly observed in SyXBs and usually ascribed to the presence of structures in the wind of the red giant companion (see, e.g., Yungelson et al. 2019, and references therein). It is well known that the slow \( \left( v_{\text{wind}} \sim 10 \text{ km s}^{-1} \right) \) dusty winds of cool evolved stars are strongly inhomogeneous and contain large scale structures such as clumps and shells (for a recent review see Decin 2021). The structures have been directly resolved in the atmospheres of some nearby M-type giants using imaging and interferometric observations. Adam & Ohnaka (2019) show that the clumpy dusty clouds are present already within a few stellar radii in the wind of IK Tau, while the asymmetric dust emission extends to outer wind regions. The clumpy structures have typical density enhancements of a factor of \( \sim 3 \) compared to the surrounding wind. Adam & Ohnaka (2019) measured the extent of two huge clumps which have a size of \( \approx 80 \) mas. At the distance 260 pc to the star, the measured clump size corresponds to \( \approx 10^6 \) km. Assuming a typical orbital velocity of \( 10 \text{ km s}^{-1} \) for a NS around a red giant with a period of several years, it would take the compact object about 1 yr to cross a similarly extended structure. It is thus possible that the enhancement in the mass accretion rate that was needed by IGR J17329−2731 to finally turn on as a SyXB has been caused by the NS interaction with one (or more) large stellar wind clump. If the orbit of the system is as large (or larger) than that measured for 4U 1700+24 (Hinkle et al. 2019), then we might conclude that in the past the NS has never being in contact with similarly large structures and thus no X-ray emission could ever be detected before 2017. According to this scenario, it is possible that IGR J17329−2731 will stop shining in X-rays over the time scale of one to few years, as soon as the orbit of the compact object does no longer intersect a massive stellar wind clump.

The XRT monitoring of IGR J17329−2731 also revealed the presence of intriguing obscuration events, lasting a few days (see Fig. 6 and 7). The spectral properties observed during these events are remarkably similar to those commonly recorded during X-ray eclipses. However, it is unlikely that the NS in IGR J17329−2731 was eclipsed by its giant companion during the XRT observations. The main argument against this possibility is that the obscuration events revealed by XRT have different durations and they repeat irregularly for times in less than \( \sim 100 \) days (to be compared to the typical orbital period of SyXBs of the order of years). A more likely possibility, already explored in the case of supergiant X-ray binaries where the NS is accreting from the clumpy wind of its massive companion, is that the NS in IGR J17329−2731 was temporarily obscured by a stellar wind structure located along the line of sight to the observer (see, e.g., Bozzo et al. 2011; Martínez-Núñez et al. 2017, and references therein). As we considered above that a single massive clump could be at the origin of the onset of the X-ray activity from IGR J17329−2731, we can assume that the obscuration events are most likely triggered by the presence of substructures within the large clump or in the surroundings. There are indications, indeed, that atmospheric structures of red giants could change on the time scale of weeks as confirmed by both observations and hydrodynamic models (see Höfner & Freytag 2019, and references therein). Furthermore, their stellar winds are permeated by shock fronts which are induced by stellar pulsations and/or convection (see, e.g., Perrin et al. 2020). The presence of a NS embedded in the wind further perturbs the atmospheric morphology with its orbital motion as well as with the effect of wind ionization by the X-ray radiation (see, e.g., Bozzo et al. 2021, and references therein). We can thus envision the possibility of the smaller scale structures being present in the wind or within the clump to induce the temporary obscuration events, as well as the short flares observed by XRT. The detection of emission lines corresponding to (at least) He-like and H-like iron further supports this scenario as the ionization of the stellar wind material is most likely occurring in the vicinity of the NS due to the X-ray radiation.

DATA AVAILABILITY
The data underlying this article are publicly available from the XMM-Newton, NuSTAR, Chandra, and Swift archives and processed with publicly available software.

ACKNOWLEDGEMENTS
We thank the anonymous referee for swift comments that helped us improve the paper. The Swift data of our monitoring campaigns on IGR J17329−2731 were obtained through contract ASI-INAF I/004/11/5 (PI P. Romano). PR acknowledges financial contribution from contract ASI-INAF INAF I/037/12/0. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester (see Evans et al. 2007, 2009).

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