

The giant outburst of EXO 2030+375

I. Spectral and pulse profile evolution

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ABSTRACT

The Be X-ray binary EXO 2030+375 went through its third recorded giant outburst from June 2021 to early 2022. We present the results of both spectral and timing analysis based on NICER monitoring, covering the 2–10 keV flux range from 20 to 310 mCrab. Dense monitoring with observations carried out about every second day and a total exposure time of ~ 160 ks allowed us to closely track the source evolution over the outburst. Changes in the spectral shape and pulse profiles showed a stable luminosity dependence during the rise and decline. The same type of dependence has been seen in past outbursts. The pulse profile is characterized by several distinct peaks and dips. The profiles show a clear dependence on luminosity with a stark transition at a luminosity of $\sim 2 \times 10^{36}$ erg s⁻¹, indicating a change in the emission pattern. Using relativistic raytracing, we demonstrate how anisotropic beaming of emission from an accretion channel with a constant geometrical configuration can give rise to the observed pulse profiles over a range of luminosities.

Key words. stars: neutron – X-rays: binaries – X-rays: individuals: EXO 2030+375

1. Introduction

Accreting Be X-ray binary systems (BeXRBs) are a common target for the study of accretion onto highly magnetized neutron stars as they have the advantage of being both common and going through a wide range of luminosities during an outburst (Reig 2011; Okazaki et al. 2013; Vybormov et al. 2017). Depending on the mass-accretion rate, these systems feature discrete luminosity states associated with changing properties of the X-ray emission regions in the accretion channel closer to the surface of the neutron star, the “accretion column”. These changes are thought to be related to the geometry of the accretion column due to the different physical mechanisms with which the accreted matter is decelerated from its free fall speed of $\sim 0.5c$ (see, e.g., Becker et al. 2012). Generally, two distinct types of outbursts are

observed in BeXRBs: regular Type I outbursts that occur close to periastron and last for about 20–50% of the system’s orbital period, and giant Type II outbursts. The latter ones can span up to two orders of magnitude in luminosity.

One prototypical system that shows both types of outbursts very prominently is EXO 2030+375 (see Fig. 1), a neutron star with a B0 Ve companion (Reig & Coe 1998). The source was discovered with European X-ray Observatory Satellite (EXOSAT) in 1985 during a Type II outburst showing clear pulsations with a period of 43 s (Parmar et al. 1989a). These early observations also showed orbital modulation of the pulse period, establishing its 46 d orbit (Wilson et al. 2008). This orbital motion results in regular Type I outbursts around the periastron passage (Stollberg et al. 1994). The luminosity of Type I outbursts and phase shift with respect to the periastron

varies with time and is influenced by the preceding giant outburst, possibly due to changes in the circumstellar disk (Laplace et al. 2017). Since its initial discovery, EXO 2030+375 has continued to display regular Type I outbursts and pulsations down to 3–38 keV luminosities of $\sim 8 \times 10^{34}$ erg s $^{-1}$ (Furst et al. 2017).

The early EXOSAT observation already covered a factor of ~ 100 in luminosity and revealed a stark variability of pulse profiles with luminosity. At 1–20 keV luminosities upward of $\sim 2.4 \times 10^{37}$ erg s $^{-1}$, the profiles are dominated by a single broad peak, which initially becomes sharper and more asymmetric with lower luminosity before a secondary peak becomes dominant when reaching a luminosity of $\sim 2.8 \times 10^{35}$ erg s $^{-1}$. Additionally, as the luminosity decreases to around $\sim 2.8 \times 10^{36}$ erg s $^{-1}$, a distinct “notch” forms in the profile (Parmar et al. 1989b)¹. This pattern of variability with luminosity has been repeated with little variation by all Type I and Type II outbursts (Wilson et al. 2008; Epili et al. 2017). Consequently, observations by the Rossi X-ray Timing Explorer (RXTE) during one of the Type I outbursts showed no significant change in the pulse profiles compared to previous EXOSAT observations at a comparable luminosity, indicating the remarkable consistency of the luminosity-dependent pulse profiles in EXO 2030+375 (Wilson et al. 2008). A second giant Type II outburst was detected in 2006 (Klochkov et al. 2007), again showing the familiar dependence on the luminosity of the pulse profile. Concerning the energy dependence of the profiles Parmar et al. (1989b) initially noted a resemblance of the high-energy profiles to those at lower luminosities. Subsequent phase-resolved spectral analysis revealed significant changes in the parameters of the spectral continuum with the pulse phase (Klochkov et al. 2008). In July 2021, a third Type II outburst was detected. This outburst was monitored by multiple X-ray missions, including, the Neutron Star Interior Composition Explorer (NICER), the Nuclear Spectroscopic Telescope Array (NuSTAR), *Swift*, *Chandra*, and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), among others. The goal of this paper is to make use of this unprecedented data coverage on the complex but reproducible pulse profile behavior of EXO 2030+375 and to provide insight into possible emission geometries by expanding on early modeling attempts. Although some of the data presented here have been published by Tamang et al. (2022), these authors only briefly touched on the evolution of the pulse profile and its physical interpretation. Here, we aim to provide a more detailed analysis in the following. We begin our paper with an overview of the available NuSTAR and NICER observations and the respective data extraction, continuing with a brief look at the spectral evolution of EXO 2030+375 over its outburst in Sect. 3. The main part of the paper focuses on the evolution of the pulse profile, starting with an overview of the NICER profile shape evolution with the luminosity and energy seen with NuSTAR in Sect. 4. In Sect. 5.1 we explain how we applied the physical light-bending code to our two specific observations and expanded our pulse profile analysis to all observations through the use of a simplified phenomenological model in Sect. 5.2. Finally, we discuss our results in Sect. 6. An accompanying paper, Ballhausen et al.

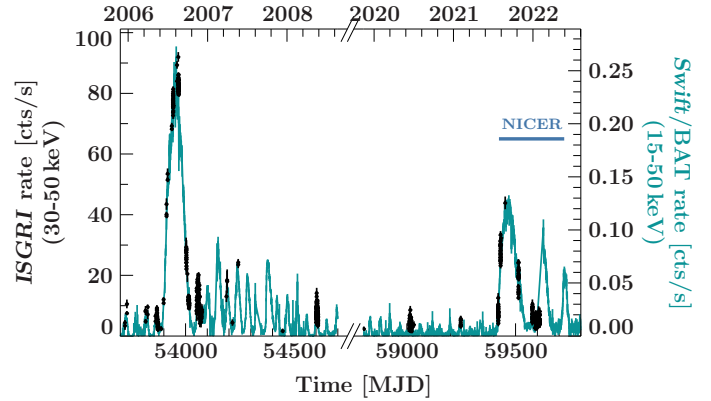


Fig. 1. Long-term light curve of EXO 2030+375 in the 30–50 keV band as seen with INTEGRAL in black and the *Swift*-BAT light curve in teal. For comparison, time ranges around the two most recent Type II outbursts are shown. INTEGRAL data were binned by Science Window, while for *Swift*-BAT the daily light curve was used. Marked by a horizontal bar is also the time range covered by the NICER monitoring used in this work. See Fig. 2 for the NICER light curve of the 2021 outburst.

(2024, hereafter Paper II), will focus on broadband spectroscopy at the outburst peak and at the end of the outburst with NICER and NuSTAR.

2. Observations and data reduction

2.1. NICER

Figure 1 shows the long-term light curve of EXO 2030+375 in the 20–80 keV band measured with the INTEGRAL Soft Gamma-Ray Imager (ISGRI) and *Swift*-BAT. The figure shows the 2006 Type II giant outburst, which was followed by a sequence of lower flux Type I outbursts with a decaying flux. In 2021, the start of a new Type II outburst was detected by the Monitor of All-sky X-ray Image (MAXI) (Nakajima et al. 2021). We triggered NICER monitoring of the outburst, which began monitoring EXO 2030+375 on 2021 August 5, and continued with regular observations of decreasing cadence until at least 2023 March ($\sim$ MJD 60016). For this work, we include all observations until ObsID 4201960176 (MJD 59609), amounting to an exposure time of ~ 160 ks. Figure 2 shows the resulting NICER light curve over the course of the outburst. Some gaps in the monitoring during the rise and decline of the outburst are an inevitable result of the visibility constraints that come with NICER’s location on board the International Space Station (ISS). We extracted the data using the NICER data analysis pipeline, as part of Heasoft 6.31.1 with CALDB version 20220413.

For data reduction, we used the default filter criteria used by *nicerl2*. Background spectra were generated using the *3C50* model². We explored the use of alternative background models, but found the *3C50* to produce the most consistent background spectra. We further note that the source was bright enough that the choice of background model did not affect the results of our spectral analysis in a significant way. Unless otherwise stated, we restricted our spectral analysis to the 0.5–10 keV energy band, where the NICER calibration is most reliable.

¹ We note that the distance of the companion of EXO 2030+375 derived from *Gaia* Data Release 3 (DR3) is $2.4^{+0.5}_{-0.4}$ kpc (Bailer-Jones et al. 2021). This distance is significantly shorter than that previously assumed (7.1 ± 0.2 kpc Wilson et al. 2002). As such, most of the literature so far has overestimated the distance to EXO 2030+375 and thus its luminosity. See Appendix B for a discussion. For this work, unless stated otherwise, we consistently give luminosities based on the updated *Gaia* DR3 distance.

² https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/background/

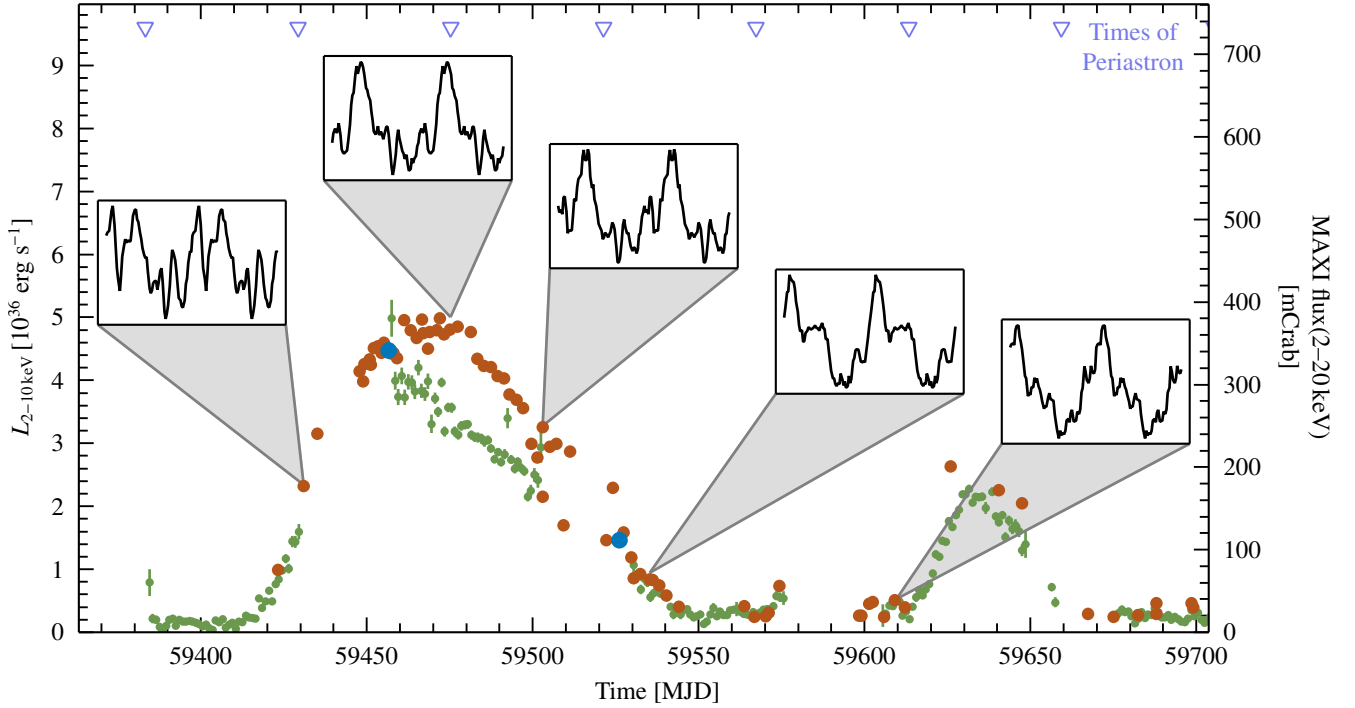


Fig. 2. Light curve of the outburst as seen by NICER with each point corresponding to one observation. The luminosity of each observation is derived from the spectral fits described in Sect. 3. The daily MAXI light-curve of the same period is shown in green. Observations with quasi-simultaneous NuSTAR points are marked in blue. Overlaid are five of the pulse profiles at different times over the outburst. The purple markers at the top indicate the times of periastron passage using the orbital solution by Wilson et al. (2002).

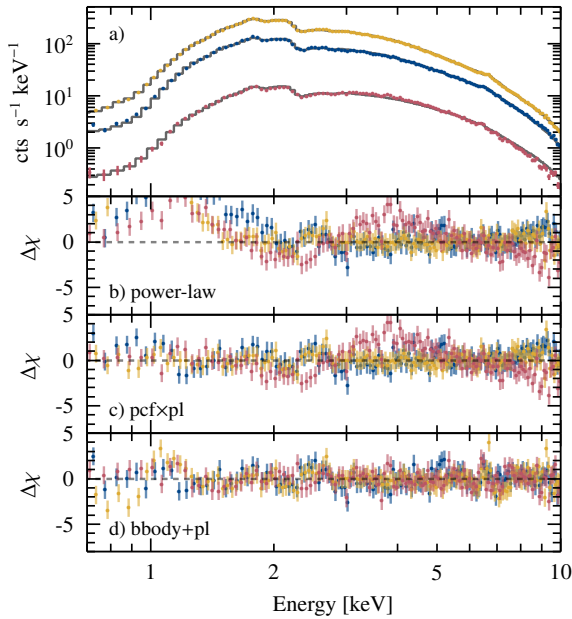


Fig. 3. Spectrum of the rise (ObsID 4201960102), peak (ObsID 4201960113), and decline (ObsID 4201960150) of the outburst of EXO 2030+375 and their best fit with the bbody+pl model in blue, yellow, and red respectively. The lower panels show the residuals for fits with an absorbed power law with an iron $K\alpha$ line emission and with an additional black body or partial covering component.

2.2. NuSTAR

In addition to the NICER monitoring, we also performed two NuSTAR observations. The first observation was performed

on 2021 August 30, when it became apparent that the outburst approached its peak, and the second on 2021 November 8 during the decline, when NICER began to detect significant changes in the pulse profile. These two observations, with ObsID 80701320002 and ObsID 90701336002, have exposure times of 32 ks and 23 ks, respectively. Light curves for various energy bands were generated using version 0.4.9 of the *nupipeline* and CALDB v20211020. Pulse profiles were constructed from barycentered light curves corrected for dead time with 0.5 s resolution. See the accompanying Paper II for a detailed discussion of these two observations. A detailed description of the data reduction is given in Paper II.

3. Spectral evolution over the outburst

To put the evolution of the pulse profile in the context of the spectral evolution over the course of the outburst, we described the NICER spectra with an empirical continuum model. A continuum model consisting of an absorbed power law with a Gaussian iron line, using abundances by Wilms et al. (2000) and cross sections by Verner et al. (1996), shows significant residuals in the soft X-rays. We addressed those in two ways, either with an additional blackbody component, as used among others by Reynolds et al. (1993), or with an additional partial covering absorber as also applied before to this source by Naik & Jaisawal (2015). A comparison of residuals between the three models during the rise, peak, and decline of the outburst is shown in Fig. 3. Both the added blackbody and the partial coverer³ lead to a significantly improved description of the data with a good description of the soft excess below ~ 1.4 keV. The remaining residuals around 2 keV are likely the result of calibration uncertainties

³ <https://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/>

Table 1. Mean and standard deviation of reduced χ^2 values for the best fits of the three considered models to the NICER observations studied in this work.

	pow	pow+pcf	pow+bb
Mean red. χ^2	2.31	1.61	1.02
Std dev. red. χ^2	0.95	0.91	0.35

around the Au-edge in the NICER effective area (Vivekanand 2021).

To track the spectral change over the outburst we chose to model the soft excess around 1 keV with a black body emission component, as this led to slightly improved fit statistics compared to the partial coverer. However, we caution that the additional soft emission components cannot be fully disentangled from a geometrically complex and potentially ionized absorber and that the spectrum is likely affected by both. An overview of the average fit statistic for the three tested models is shown in Table 1. The resulting evolution of the spectral parameters is shown in Fig. 4. The panel on the right displays the correlation of spectral parameters with luminosity. Both the hardness ratio and the photon index show a clear trend toward a softer spectrum with increased flux, while the fitted hydrogen column density switches from a negative to a positive correlation as luminosity increases. There is a clear jump in the temperature and size of the soft component around a luminosity of 10^{36} erg s $^{-1}$, which also coincides with an inversion in the evolution of the photon index, Γ , and the absorption column, N_H . The source reached this luminosity close to the end of the outburst (Fig. 2). While one could interpret the change in the blackbody component as a transition from accretion disk emission to emission coming from the neutron star surface, we repeat that the soft spectrum is likely more complex than modeled here and should therefore be interpreted with caution.

Figure 5 puts the spectral behavior of EXO 2030+375 during the 2021 Type II outburst in the context of the Type II outburst observed in 2006 with RXTE. The RXTE data of EXO 2030+375 have been studied by various authors but here we focus on the evolution of spectral hardness with luminosity as presented by Epili et al. (2017). These authors chose energy bands of 3–10 keV and 10–30 keV for measuring the hardness ratio and source luminosity. Due to the hard band lying outside the NICER bandpass and the rather complex evolution of the spectral shape of EXO 2030+375, their results are complementary but not directly comparable to the behavior we observed. From the 2006 RXTE data we, therefore, construct hardness ratios and luminosity estimates using the same energy bands as for our analysis of the NICER data. Additionally, we show in the lower panel of Fig. 6 the hardness ratio as defined by Epili et al. (2017). To determine the fluxes, we used the same spectral model that we also used for the 2021 data, with the exception of the blackbody components, which are not required in the RXTE/PCA energy range of 2–60 keV. Using consistent energy bands and estimated distances, we found that the overall dependence of the spectral hardness on the X-ray luminosity is very similar between the 2006 and 2021 giant outbursts, although the RXTE data span a larger luminosity range overall and the 2006 outburst had a higher peak luminosity. While we note subtle differences in the shape of the turnover in comparison to Epili et al. (2017) due to the different energy bands, the transition in spectral behavior around $L_{2-10\text{ keV}} \sim 10^{36}$ erg s $^{-1}$ from a positive to a negative

correlation between luminosity and hardness is consistent and strong evidence for a transition toward supercritical accretion (Postnov et al. 2015).

4. The varying pulse profile of EXO 2030+375

4.1. Pulse-profile evolution with luminosity

In addition to systematic spectral changes with luminosity, EXO 2030+375 is known for similarly remarkable changes in its pulse profile. Due to the strong spin-up of up to $\sim 5 \times 10^{-8}$ s s $^{-14}$, leading to the period decreasing from 41.29 s to 41.22 s over the course of the outburst, we determined the local pulse period for each observation by epoch folding the orbit-corrected light curve and aligning the profiles through cross-correlation with respect to the profile of the preceding observation. To study how the average pulse profile changes with luminosity, we normalized the pulse profile for each observation in count rate, such that the peak count rate equals 1. Color coding of this normalized count rate allows us to compare the different pulse profiles in a pulse profile “map”, in which each row represents the profile at a given average count rate of the observation. This map is shown in Fig. 7. We note that the map contains profiles from both the increase of the outburst and the decrease of the outburst (although due to our observational cadence, the outburst decay dominates). We did not see a difference in profile between the increase and decay, indicating that the change of profile depends only on the source luminosity. As shown in Fig. 7, as the source luminosity increases, there is a clear change in strength between the first peak at phase 0 and the second around phase 0.25. In contrast, the overall structure of the profile between phases 0.5 and 0.9 is comparably stable. There also appears to be little further change in the profile above a count-rate of ~ 400 cps, corresponding to a luminosity of $\sim 3 \times 10^{36}$ erg s $^{-1}$. A very stable feature of the profiles is also the dip around phase 0.7, which only seems to lose its shape toward the lowest luminosities, where low statistics limits the usable phase resolution.

In addition to these changes with luminosity, the profile also depends strongly on energy. To extend the energy range to harder photons, we included the NuSTAR data in this study. Consequently, we concentrate on the pulse profile during the peak of the outburst and during the end of the outburst, at X-ray luminosities of $\sim 1.6 \times 10^{36}$ erg s $^{-1}$ and $\sim 4.78 \times 10^{36}$ erg s $^{-1}$, respectively. Figure 6 shows the pulse profiles for selected energy bands and the hardness ratio as a function of the pulse phase. The corresponding complete phase-energy maps of the same observations are shown in Fig. 8. Here, only strictly overlapping GTIs are used to keep especially the pulsed fraction between instruments comparable. We found an evolution of the first peak at phase 0 and the wings around the dip at phase 0.7, which both seem to flatten toward the highest energies, leading to a simpler profile that is dominated by a single component. This trend to a less structured profile is present in both the high- and low-flux observations.

Interestingly, when looking at the hardness ratio in Fig. 6, around phase $\phi = 0.07$ – 0.15 there seems to be a significant difference between the two observations. This phase corresponds to the decline of the first peak and appears significantly softer than surrounding phase bins during the first observations and harder in the second observation. This is discussed in more detail in Paper II, where pulse phase-resolved spectroscopy reveals changes in the blackbody emission around this phase.

⁴ <https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html>

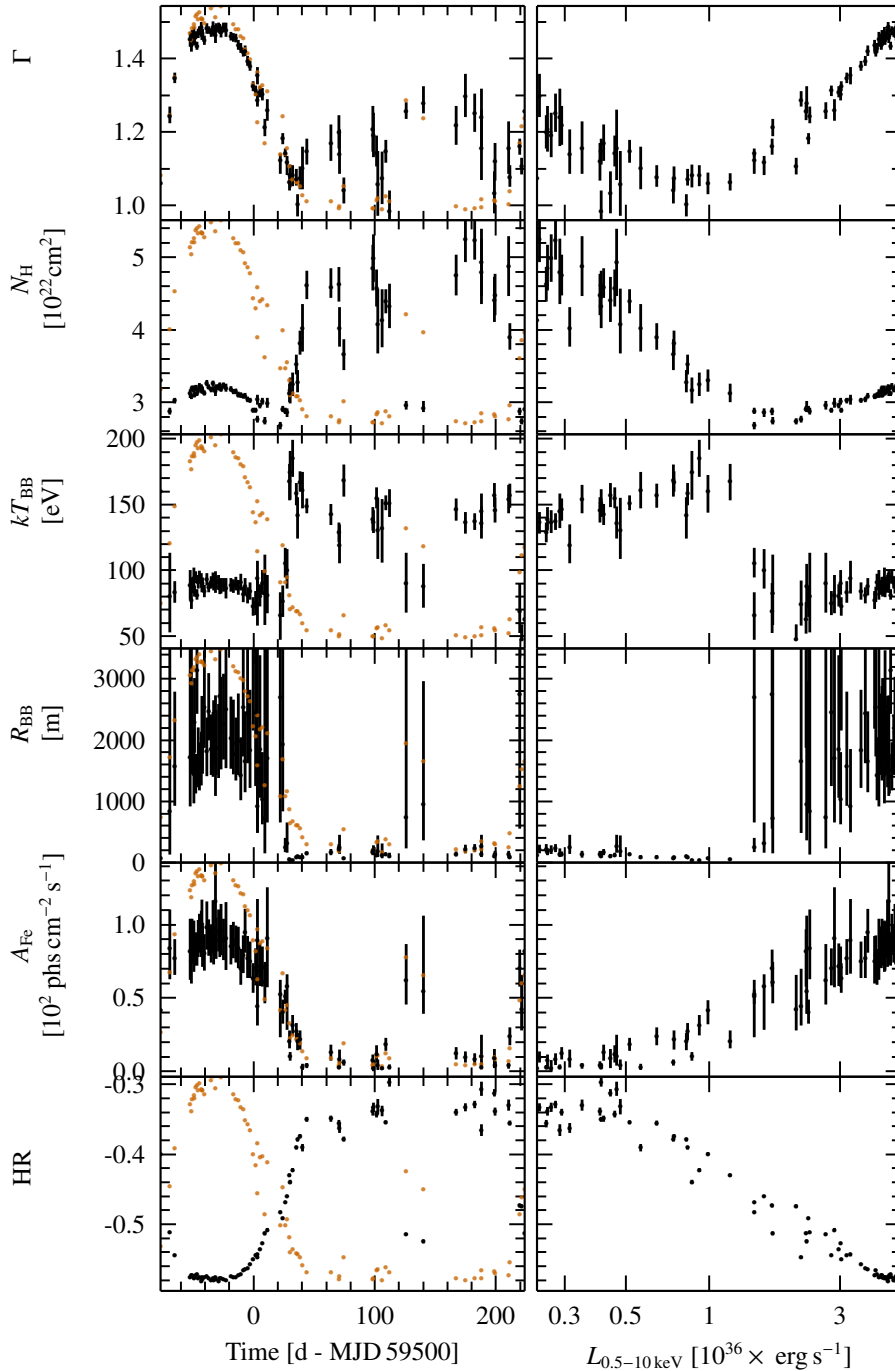


Fig. 4. Evolution of the 0.5–10 keV flux, hardness, and main spectral parameters over the course of the 2021 outburst. The left panel shows the evolution over time and the right panel shows how these parameters depend on luminosity. The orange data points in the left panel represent the light curve over the course of the outburst. The hardness is defined as $(H - S)/(H + S)$ where H is the count rate in the 0.5–2 keV band and where S is the count rate in the 2–10 keV band. Each point corresponds to one observation.

4.2. Sharp dip at low luminosity

A feature in the pulse profile that is only visible during observations at low luminosities of $\sim 2.0 \times 10^{35} \text{ erg s}^{-1}$ is a sharp dip at phase 0.75. As such, it is only detected in some of the last observations, most prominently for ObsID 4201960165, which is shown in Fig. 9. The dip only spans a phase interval of 0.05 and is not resolvable in observations with low statistics. It is accompanied by a sharp change in the hardness ratio, marked by a hardening during the center of the peak and a softening during its flanks. The feature has been observed in several previous observations and has been attributed to absorption by a phase-locked accretion stream (Reig & Coe 1999; Naik & Jaisawal 2015; Ferrigno et al. 2016; Fürst et al. 2017; Jaisawal et al. 2021). The complex evolution of the pulse profile might be driven by a complex ionization profile of the absorbing medium.

5. Modeling the pulse profile of EXO 2030+375

5.1. Physical pulse profile modeling

In order to gain more physical insight from the measured pulse profiles, we applied the relativistic light bending code developed by Falkner (2018), which was previously used by Iwakiri et al. (2019) to successfully model pulse profiles of 4U 1626–67. In this approach we, for now, do not consider the evolution with energy and therefore focus our efforts on a narrow energy band with high count rate. We selected the NICER pulse profiles in the 3.5–4.5 keV energy band. To constrain geometrical parameters and break some of the degeneracies of the model, albeit at the cost of increased computation time, we simultaneously fitted two pulse profiles at different luminosities with the same shared column position. We chose to fit the pulse profiles of the two

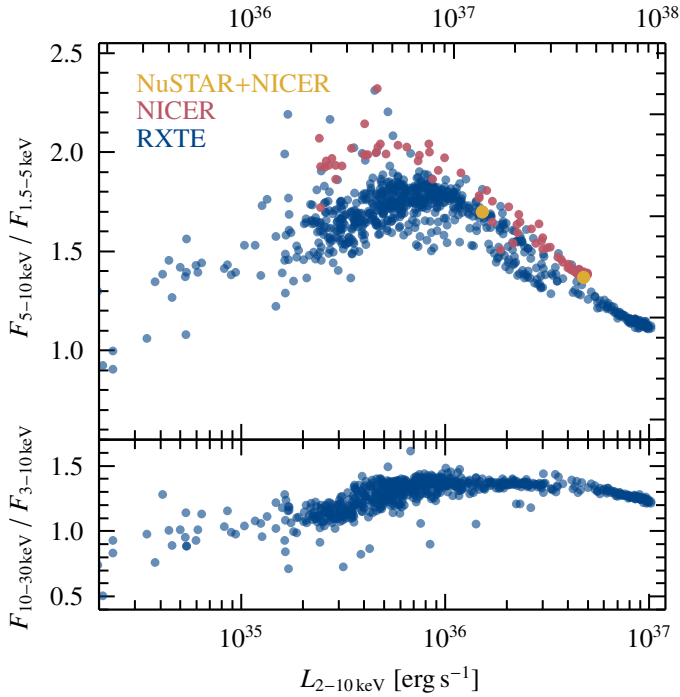


Fig. 5. Evolution of hardness, as derived from the flux ratio in the 1.5–5 keV and 5–10 keV bands. For the 2021 outburst, NICER data was used, while for the 2006 outburst we used archival RXTE data. For comparison with previous works, a distance of 7.1 kpc was used to calculate the luminosity on the upper x-axis, while 2.4 kpc was used for the lower x-axis.

NICER observations that were concurrent with the two NuSTAR observations. Expanding the analysis to a wider range of energies and times will be part of future work.

The applied model is set up as follows: Sources of emission are two cylindrical accretion columns with height h and radius r placed at arbitrary positions on the neutron star surface. Each column consists of two types of emitting surface elements – those that make up the walls and those that make up the top of each column. For both the top and the wall surfaces, we defined an emission pattern that is equal for all surface elements of one category and shared by both columns. While the column positions are constant between the two observations and assumed not to vary, the emission parameters are allowed to change between observations of varying luminosity.

This leads to four independent emission components, as we have two observations with top- and wall-emissions each. These four total emission components are each defined by a simple Gaussian emission profile. For the wall component, this Gaussian profile is perpendicular to the column axis and is therefore defined by its width σ_{wall} . This is intended to model any kind of “fan” emission pattern. The emission from the top can be inclined from the column axis. Therefore, its Gaussian emission profile is centered at an angle μ_{cap} and has a width of σ_{cap} . This can mimic the butterfly pattern of a “pencil” beam predicted by Basko & Sunyaev (1975) among others.

The location of the two columns is determined by two angles: the polar angle Θ , defined as the angle between the column and the rotation axis of the neutron star and the azimuthal angle ϕ . Figure 10 provides a depiction of the neutron star with two accretion columns and characteristic angles. We also had to set the observer’s viewing angle i with respect to the rotation axis. In order to reduce the number of free parameters, we fixed the

radius of each column at 250 m and the height at 300 m for both observations. We kept these values fixed between the two observations as their influence on the pulse profiles is minor for most geometries.

Still, we want to note at this point that the parameters of the accretion column and its exact geometry (a hollow or filled cylinder) are widely discussed in the literature, without a current consensus on the topic. We admit, however, that both the radius and the height of the column depend on the strength of the magnetic field, which in the first approximation is typically considered to be dipolar. The radius of an accretion channel near the surface of a highly magnetized accreting neutron star is expected to be small compared to the total surface area. Very approximately, it can be estimated from the magnetospheric radius, R_m , and the neutron star radius, R_{NS} , as $r_0 \sim R_{\text{NS}} \sqrt{R_{\text{NS}}/R_m}$ (Lamb et al. 1973). In the case of EXO 2030+375, the magnetic field remains unknown, although a possibility of a shallow absorption line in the spectra was discussed at energies ~ 10 –60 keV (Klochkov et al. 2007, and Paper II), this feature has not been confirmed as a cyclotron line so far. Alternative methods of field estimates provide a rather broad range of values, $B \sim 0.5 \times 10^{11}$ – 10^{13} G (Tamang et al. 2022). It translates to the column radius of ~ 200 –800 m for the accretion luminosity of $\sim 10^{36}$ erg s $^{-1}$ and canonical neutron star parameters (it also depends on the parameters of the accretion flow above the magnetospheric radius, which remain largely unknown as well; see, e.g., Eq. (18) of Lamb et al. 1973 and Eq. (23) of Becker et al. 2012).

The height of the accretion column is even more uncertain. At luminosities above the critical one, it is expected that the radiation pressure is capable of initiating deceleration above the surface of the neutron star (Basko & Sunyaev 1976). The heights of the accretion columns typically discussed in one-dimensional analytical modeling are ~ 10 km (see, e.g., Basko & Sunyaev 1976; Becker et al. 2012; West et al. 2017). At lower, intermediate luminosities, the estimate of the accretion column height varies, spanning a few orders of magnitude. Thus, it was discussed by different authors that the emission is either produced directly at the polar caps of the neutron star (Mushtukov et al. 2015a), slightly above the surface, by ~ 100 –200 m, where matter is being decelerated by Coulomb collisions (Staubert et al. 2007) or a collisionless shock (Vybornov et al. 2017), or kilometers above the surface in the frame of a different collisionless shock model (Becker & Wolff 2022). Some analytical estimates (Becker et al. 2012; West et al. 2017) heavily rely on estimates of the magnetic field and mass accretion rate, both of which are challenging for EXO 2030+375 due to an unconfirmed cyclotron line and uncertainty on the distance (see Sect. 6). In the choice of both the height and the radius of the accretion column, we relied on the most recent two-dimensional magnetohydrodynamic simulations by Sheng et al. (2023), which demonstrated a rather low height of the accretion column even in the case of sufficiently high radiation pressure. It is important to note, however, that within the frame of the model described above, the height of the column does play a crucial role in the variation of pulse profiles.

Recently, IXPE observed EXO 2030+375 during one of its recent Type I outbursts (Malacaria et al. 2023). Importantly, the evolution of the polarization angle with pulse phase was modeled by the rotating vector model (RVM), which depends on the orientation of the magnetic dipole field. Thus, the pulsar inclination was constrained to 127.5^{+9}_{-7} . Therefore, we adopted a value of 130° as the inclination in our model, as otherwise we could only rule out low inclination angles $\lesssim 40^\circ$, as seen in Fig. 11. The

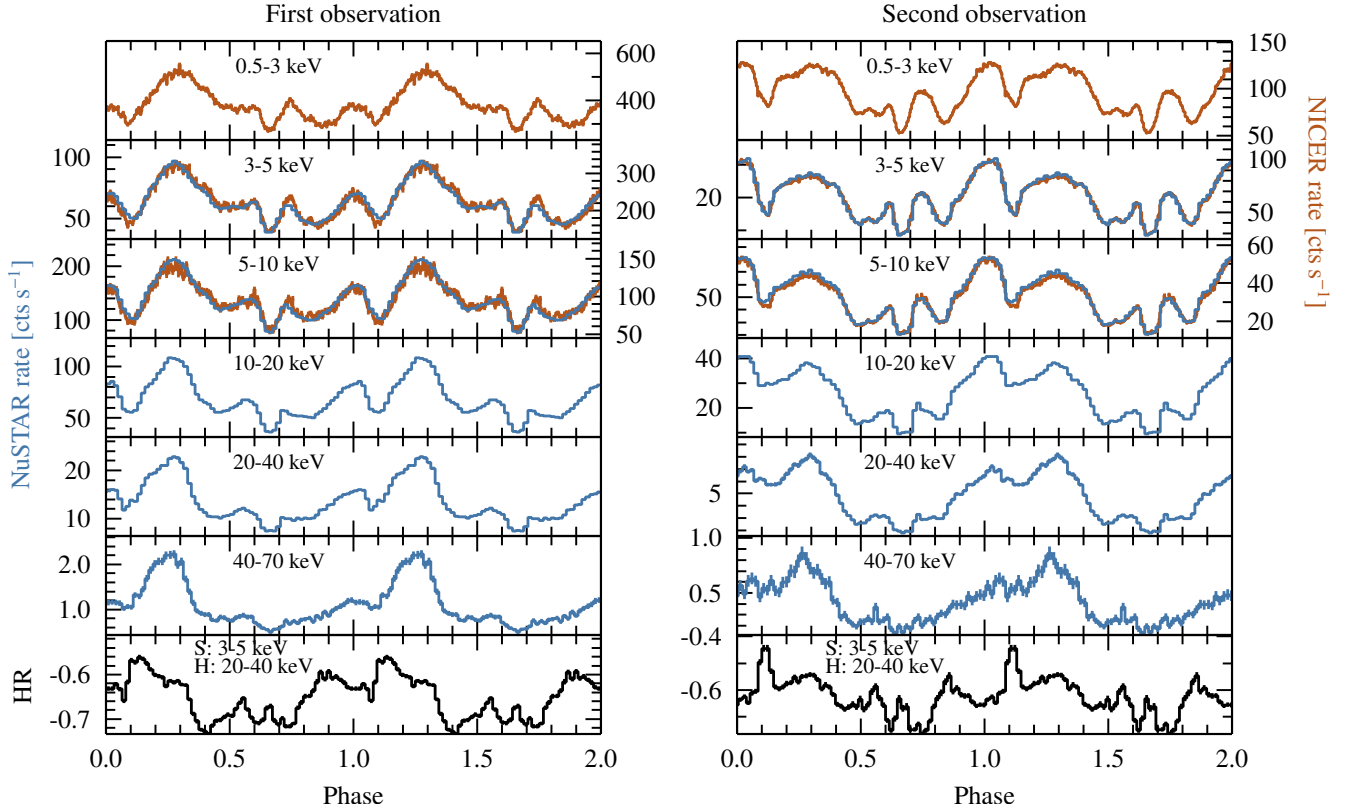


Fig. 6. Pulse profiles in different energy bands for both NICER in blue and NuSTAR in red. The left plot shows the first NuSTAR observation and the concurrent NICER pointing, while the right plot shows the second NuSTAR observation and its concurrent NICER pointing. The hardness ratio in the lowest panel is calculated from NuSTAR data as $(H + S)/(H - S)$, with the two energy bands S: 3–5 keV and H: 20–40 keV.

reliability of the RVM will be discussed toward the end of this paper.

Then finally, to calculate the observed flux for each rotation phase from the setup just described, our model projects the surface elements onto the plane of the observer, while taking relativistic light bending into account, calculates their visibility and brightness according to their emission pattern, and integrates over them. This results in a model flux for each phase bin that can then be compared with the observed data. A more detailed description of the required calculations can be found in Appendix A, in the application by Iwakiri et al. (2019), and in Falkner (2018). We found the configuration described by Table 2, with pulse and emission profiles of Figs. 12 and 13, to give a good description of the observed profiles.

Trying to extend this model to profiles corresponding to even lower luminosities by simply adjusting the normalization of the four components only lead to unsatisfactory fits, confirming that not only the strength of cap or column emission changes, but the respective emission pattern of each component as well.

The geometry found is marked by an offset between the two columns of $\sim 169^\circ$, deviating from a simple dipole geometry with two opposing columns. This is not unexpected as this is the only way to obtain the observed asymmetry of the profiles from cylindrically symmetric emission profiles in this model. An alternative would be contributions from more than two poles, which we would, however, not expect as the matter couples to the magnetic field at a radius where the dipole component dominates. While it would be possible to include more poles in our model, this would significantly increase its complexity and should only be done if required to describe the observed profiles, which is not the case for EXO 2030+375. Of note is the large uncertainty

on the width of the second cap emission in the low-luminosity observation. This can indicate that the majority of this emission does not reach the observer and is therefore only weakly constrained by the data. The given statistical uncertainties depend on reliable fit convergence and are therefore likely underestimated.

5.2. Empirical pulse profile fitting

The evolution of the relative intensities of the individual peaks in the pulse profile, visible in Fig. 7, led us to investigate the evolution of the pulse profile over the full luminosity range. Due to the complexity of the physical model presented in the previous chapter and the large amount of pulse profile data available through NICER, only a simple empirical model was applied to the profiles of all observations. We settled on the sum of several Gaussian emission features as a simple model to quantify the profile evolution and again apply this model to the 3.5–4.5 keV energy band. By visual inspection we found that six Gaussian components reproduce the basic pulse profile morphology; however, to reliably model the profiles for all luminosities, eight Gaussians were necessary (see Fig. 14). As each Gaussian is functionally identical, we restricted the position of each of them to a certain phase range to avoid components switching positions, thus hampering convergence of the applied fitting algorithm.

The absolute flux evolution is already reflected by the light curve, so we fitted only the relative strengths of the emission components and possible phase shifts. Using systematic uncertainties of five percent on the count rate leads to flat residuals around one for most observations. An overview of the fit results is shown in Fig. 15. We see the second peak rapidly gaining

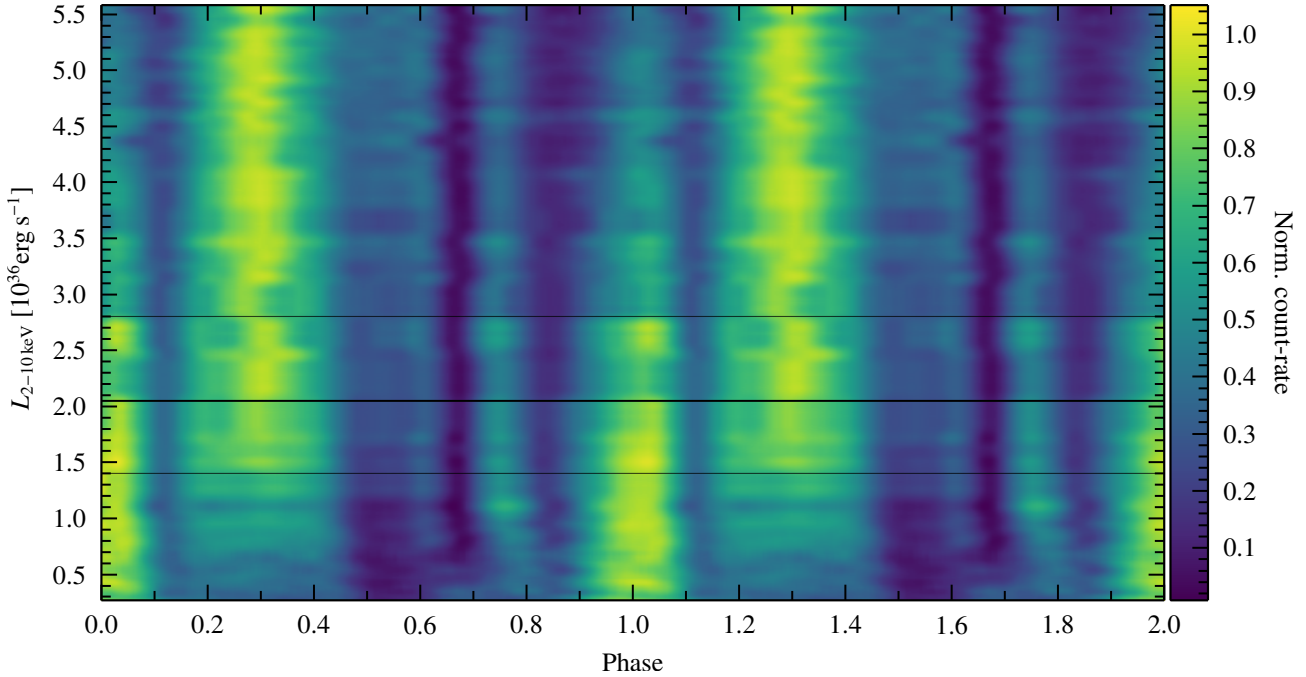


Fig. 7. Pulse profile map scaled to range from zero to one for all included NICER observations sorted by their respective luminosity. This figure illustrates the luminosity dependence of the NICER pulse profiles. The thick black line indicates luminosities where the profile shows marked changes, and the thin lines serve as markers to indicate the approximate luminosity range over which the changes take place (see the Sect. 4.1 for more information).

strength toward higher luminosity, reaching a plateau around $\sim 3 \times 10^{36} \text{ erg s}^{-1}$ or a NICER count rate of $300 \text{ counts s}^{-1}$. The first peak, on the other hand, more steadily loses its dominance toward higher luminosity, whereas the remaining features stay mostly constant. This behavior is consistent with that seen in Fig. 7.

In addition to the description with Gaussian components, we followed the procedure of [Alonso-Hernández et al. \(2022\)](#) and separated the profiles into its sinusoidal Fourier components. [Alonso-Hernández et al. \(2022\)](#) identify pattern in the energy dependencies of the first three Fourier components to categorize X-ray pulsars into one of three types. For both NuSTAR observations EXO 2030+375 closely resembles sources of their Type 2, such as Cen X-3. However, we found that the change in the profiles in EXO 2030+375 with luminosity results only in shifts in the phase offset of the Fourier components, whereas their respective amplitudes changed little. This is a consequence of the fact that individual Fourier components do not correspond to individual peaks in the profile, but rather model the profile as a whole. From this we conclude that the classification of [Alonso-Hernández et al. \(2022\)](#), which only takes into account the amplitude of these features not their position, is insufficient to describe such variability as seen in EXO 2030+375. For this reason, we will not discuss such a decomposition into Fourier components in more detail here.

6. Discussion and conclusions

In this paper, we have shown that the evolution of the spectrum, specifically the hardness ratio, over the course of this outburst follows the same luminosity dependence as seen in previous outbursts ([Epili et al. 2017](#); [Reig & Coe 1999](#)). The observed softening with higher luminosity is seen in many BeXRBs ([Reig & Nespoli 2013](#)) and is interpreted as a sign

that the source has exceeded its critical luminosity. A proposed explanation is the increased emission height, where photons can escape the accretion column with increasing luminosity, as this would reduce the efficiency of bulk Comptonization ([Becker et al. 2012](#)). Although this would contradict the assumption of a constant column height made while modeling the pulse profiles, we have seen that the emission height has only very little effect on the observed profiles and would primarily affect the spectral formation. Alternatively a reduced fraction of photons interacting with the stellar surface as the emission regions increase with increases in luminosity ([Postnov et al. 2015](#)), can lead to the observed softening.

Similarly, the evolution of the pulse profile with luminosity fits remarkably well to what has been seen in previous Type I and Type II outbursts ([Parmar et al. 1989b](#); [Klochkov et al. 2008](#); [Naik & Jaisawal 2015](#); [Epili et al. 2017](#)).

Even the sharp dip in the pulse profile, with accompanying change in the hardness ratio, studied in detail by [Ferrigno et al. \(2016\)](#) reappears again at low luminosities. This feature was already seen with RXTE, which provided the necessary time resolution and effective area to resolve it ([Reig & Coe 1998](#)). In subsequent observations, this dip was attributed to obscuration of the emission region by a phase-locked accretion stream ([Jaisawal et al. 2021](#); [Ferrigno et al. 2016](#)). As the accretion geometry is determined largely by the geometry of the magnetic field, this indicates a very stable B -field configuration over almost four decades, unaffected by repeated periods of accretion and quiescence.

Several attempts have been made at modeling the pulse profiles and reconstruction of the underlying emission geometry of accreting magnetized neutron stars ([Bulik et al. 1995](#); [Kraus et al. 1996](#); [Sasaki et al. 2010, 2012](#); [Caballero et al. 2011](#); [Cappallo et al. 2019, 2020](#); [Roy et al. 2022](#)). Roughly two approaches can be distinguished: forward modeling of

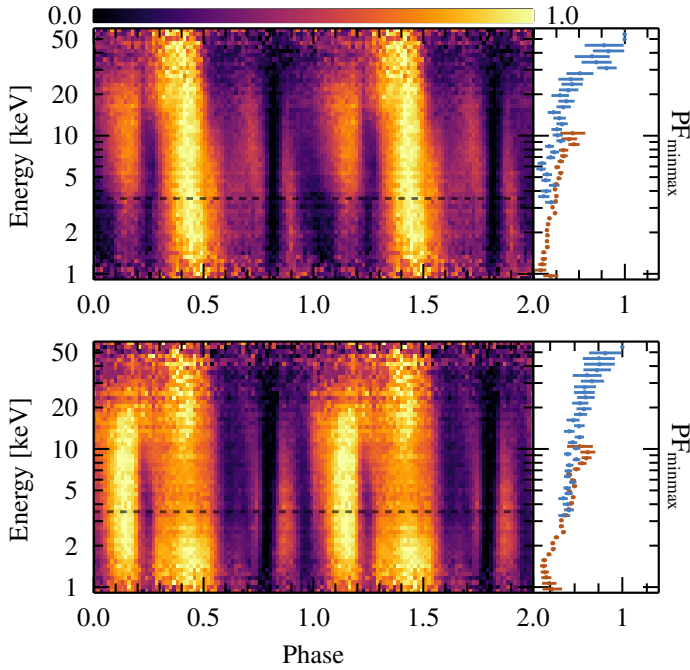


Fig. 8. Pulse profile map illustrating the energy dependence of the pulse profiles. The upper plot corresponds to the first NuSTAR observation and the corresponding NICER data, similarly for the second observation. The same data is used as for Fig. 6. Dashed, black lines indicate the transition between NICER and NuSTAR data. To the right, the pulsed fraction (PF) is plotted as a function of energy; blue is for NuSTAR data and in orange is for NICER. We defined the PF as $PF = (p_{\max} - p_{\min}) / (p_{\max} + p_{\min})$.

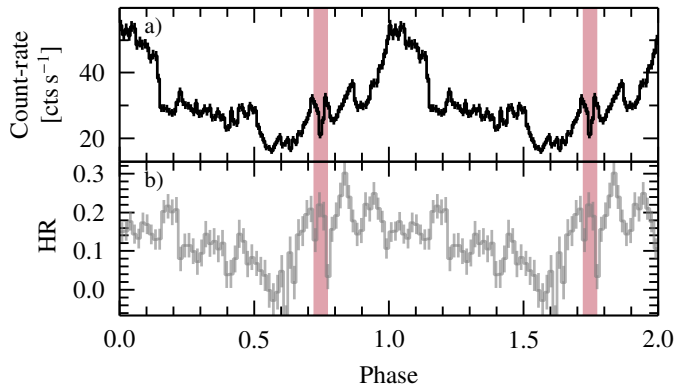


Fig. 9. Sharp dip around phase 0.75 during ObsID 4201960165 at a luminosity of $2.56 \times 10^{35} \text{ erg s}^{-1}$, taken at MJD 59570. The upper panel shows the count-rate in the full 0.5–10 keV band, while the lower one shows the change in hardness ratio defined as in Fig. 6, with 0.5–2.0 keV and 2.0–10.0 keV as soft and hard energy bands.

detected pulse profiles, and decomposition of individual emission components from the measured profiles, each requiring varying assumptions on geometry and emission profile. Applications to EXO 2030+375 are limited to early modeling work by Parmar et al. (1989b), and pulse profile decomposition by Sasaki et al. (2010).

The forward modeling approach of Parmar et al. (1989b) is similar to our work as it models the emission from two non-antipodally positioned accretion columns emitting both wall and cap components. Their emission functions are slightly different from ours, most important by using cap emission that is peaked

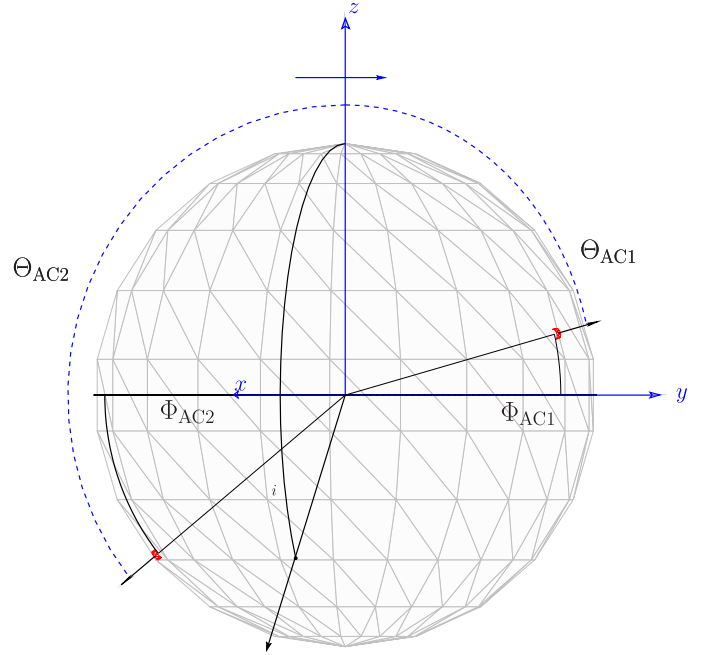


Fig. 10. Geometry of the two accretion columns (red), the rotation axis in the z -direction, and the coordinate system spanned by it (blue).

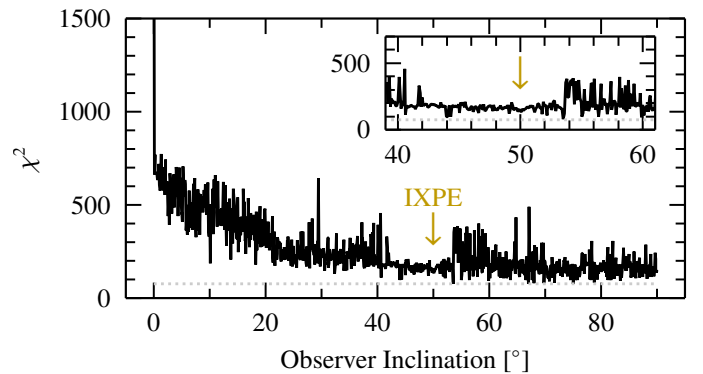


Fig. 11. Goodness of the best fit of our physical pulse profile model for a range of fixed observer inclinations. Marked is the inclination corresponding derived from IXPE data and used for our best fit (Malacaria et al. 2023). Additionally the overall best χ^2 value is indicated by the dotted gray line. The inlet focuses on the range around the IXPE value.

in the direction of the magnetic field. Most importantly, however, light bending was only included in a very simplified manner and only a rough solution fitting some of the observations was found by eye. Even more severely than in our case, this limits the degree to which their solution can be relied on to be unique and physically accurate.

Applying our light-bending model to the pulse profiles showed that the profiles can be well described by a composition wall and cap emission originating from two accretion columns. As such, we can explain the observed complexity of the profiles at different luminosities solely through a simple emission profile and column geometry without the need of a dip induced by absorption. An exception is formed by the sharp absorption dip mentioned in Sect. 4.2. In our model, the asymmetry of the pulse profiles is explained by an offset of the two columns from a simple dipole geometry, similar to previous work (Parmar et al. 1989b; Sasaki et al. 2010). We found that

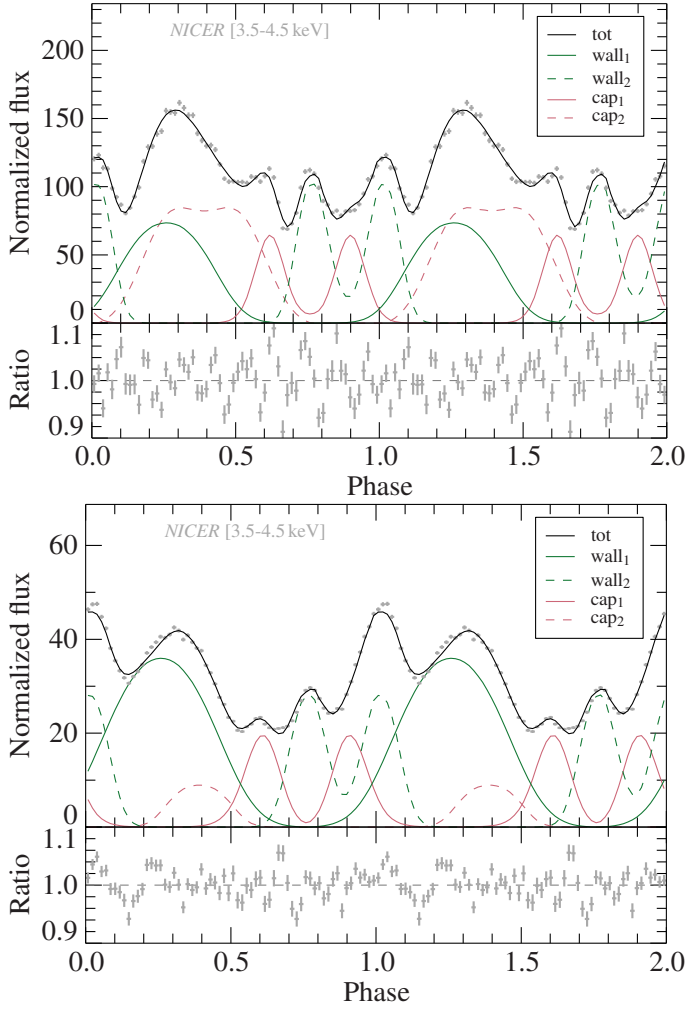


Fig. 12. Pulse profile of the high (top) and low (bottom) luminosity observation. Model components from the two columns with top (dashed) and wall (solid) emission are shown in red and green.

the angle subtended by the two column positions is 119° in our model, compared with the 110° estimate by Parmar et al. (1989b), 140° estimated by Sasaki et al. (2010)⁵. These variations should not be surprising, considering the simplified relativistic treatment of Parmar et al. (1989b) and the entirely different approach of Sasaki et al. (2010). Their decomposition of the measured profiles and reconstruction of the local emission pattern relied on the assumption of cylindrical symmetric and identical emission from two columns. This technique was first introduced by Kraus et al. (1996) and was since then applied to multiple sources. Its assumption of equal emission from the two columns fundamentally contradicts the emission profiles found in our work, and we were unable to reproduce the data when fixing the emission profiles of the two columns together.

Contrary to theoretical expectations (Davidson 1973; Basko & Sunyaev 1976), the emission pattern that we found to reproduce the observed pulse profiles displays a stronger top or “pencil” emission for the high-luminosity observation. This could be explained by reflection of downward-boosted wall emission from the neutron star surface. This component could then appear as cap emission in a model such as ours (Poutanen et al. 2013; Postnov et al. 2015). We relayed on the

⁵ For directly opposed columns in a simple dipole field this angle would be 180° .

Table 2. Best fit model parameters for the high and low luminosity states.

Parameter	L_{high}	L_{low}
i_{obs} [deg]	130	(†)
Col ₁ /col ₂ ratio	$0.43^{+0.08}_{-0.07}$	$0.767^{+0.016}_{-0.031}$
Cap ₁ /wall ₁ ratio	$0.23^{+0.06}_{-0.12}$	$0.118^{+0.025}_{-0.013}$
$i_{\text{mag},1}$ [deg]	$116.^{+26.}_{-11.}$	(†)
ϕ_1 [deg]	$324.1^{+1.1}_{-2.0}$	(†)
$\sigma_{\text{col},1}$ [deg]	$18.9^{+2.2}_{-2.0}$	$27.1^{+3.6}_{-2.4}$
$\mu_{\text{cap},1}$ [deg]	$34.^{+4}_{-8}$	$32.1^{+2.1}_{-1.7}$
$\sigma_{\text{cap},1}$ [deg]	$10.4^{+1.9}_{-1.5}$	$12.0^{+1.8}_{-1.4}$
Cap ₂ /wall ₂ ratio	0.51 ± 0.04	$0.20^{+0.22}_{-0.09}$
$i_{\text{mag},2}$ [deg]	75.6 ± 0.6	(†)
ϕ_2 [deg]	$191.3^{+0.9}_{-1.4}$	(†)
$\sigma_{\text{col},2}$ [deg]	$6.9^{+0.8}_{-0.7}$	$8.4^{+1.0}_{-0.7}$
$\mu_{\text{cap},2}$ [deg]	$53.9^{+1.8}_{-2.5}$	$39.^{+5}_{-40}$
$\sigma_{\text{cap},2}$ [deg]	$21.^{+7}_{-4}$	$10.^{+20}_{-5}$

Notes. (†) Tied together for both observations.

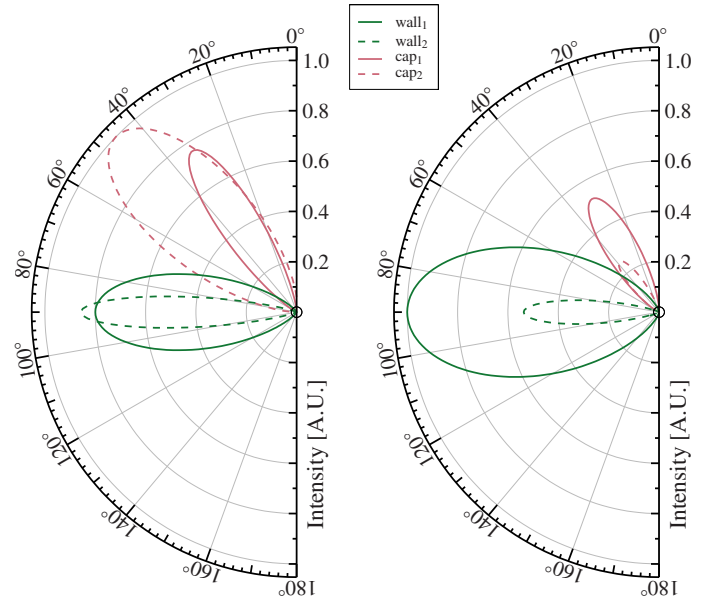


Fig. 13. Emission profiles of the different emission components giving rise to the profiles shown in Fig. 12. The left and right figure show the emission profiles for the high and low luminosity state respectively. The radial coordinate represents the integrated flux in the reference frame of the neutron star.

observer inclination determined through the application of the RVM to recent IXPE observations of EXO 2030+375 to fix this parameter in our pulse profile model (Malacaria et al. 2023). IXPE observations of the source LS V +44 17 have, however, shown that a simple application of the RVM, can lead to misleading geometries when emission components with constant polarization signal with pulse phase are ignored (Doroshenko et al. 2023). The origin of such a constant component is suspected to be reflection off of material in the disk or an outflow close to

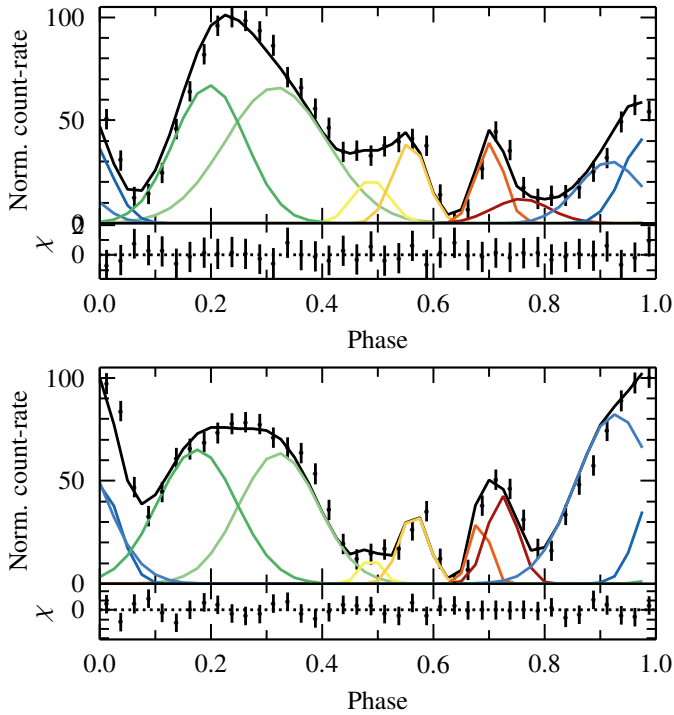


Fig. 14. Gaussian fits to observation 4201960113 (top) and 4201960150 (bottom) as an illustration of the phenomenological fitting approach. The black curve indicates the full model while the individual Gaussian peaks are shown in the same colors as in Fig. 15.

the neutron star. However, since there have been cases in which the inclination found with the RVM seems to be reliable, as it aligns well with the orbital inclination (Suleimanov et al. 2023; Mushtukov et al. 2023) and observations that do not require a phase-independent reflection component despite multiple IXPE observations (Tsygankov et al. 2023), we still consider the inclination found by Malacaria et al. (2023), to be reliable enough to use it as a basis for our pulse profile modeling. Multiple IXPE observations would still help to resolve such ambiguities, but might only be possible during the next Type II outburst. Interestingly, the assumed inclination of 50° in the decomposition of the emission pattern by Sasaki et al. (2010) fits well with the RVM results, taking into account the 180° symmetry of the problem.

Pulse phase-resolved spectroscopy has shown a significant phase dependence of the column density Reig & Coe (1998), Naik & Jaisawal (2015), Naik et al. (2013), Malacaria et al. (2023), which is currently not taken into account in our model, since only Gaussian emission profiles are assumed. Still, it should be noted that multiple “dips” in the profiles can be reproduced just from the combination of simple emission profiles and light bending, without relying on absorption. The important next step in our investigation of the pulse profiles of EXO 2030+375 is a phase-resolved spectral analysis of the combined NICER and NuSTAR data, which is presented in Paper II.

Further interpretation of the emission profiles and column geometry found should be done with care, as we cannot guarantee that we have found the unique physical solution capable of describing the measured pulse profiles. One way to verify the uniqueness of our solution would be to run algorithms that are more suited for sampling a wider range of the parameter space, since the complex parameter landscape of the problem leads to a prohibitively long burn-in and autocorrelation time when attempting to a Markov chain Monte Carlo (MCMC) analysis.

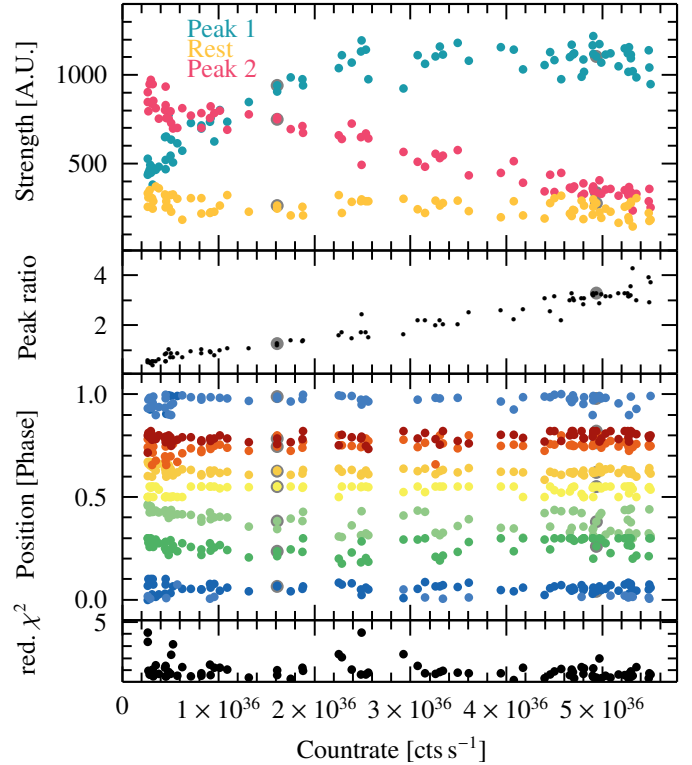


Fig. 15. Results of fitting Gaussians to the NICER pulse profiles. Top: strength of the two main peaks (red and blue) and secondary features (yellow). The first peak is defined as the sum of the first and last Gaussian, the second one as the second and third Gaussian. All other Gaussians are summed as secondary features. Middle: ratio between the strength of the secondary and primary peak. Bottom: position of all fitted Gaussians. The two observations with ObsID 4201960113 and 4201960150, selected also for Fig. 14, are marked by larger gray rings.

An important next step is to constrain the column and emission parameters used in our model through the application of self-consistent hydro dynamical models such as those of West et al. (2017) to the phase-averaged and phase-resolved spectra of EXO 2030+375. However, this is outside the scope of this work and will be part of forthcoming publications.

We can, therefore, say that it is possible to produce the complex pulse profiles of EXO 2030+375 and their evolution through simple Gaussian emission profiles that are emitted by two columns, which is far from obvious given the complex emission profiles shown in Fig. 6 in Sasaki et al. (2012). While, given the previous paragraph, we cannot yet be confident to have found the only solution that can describe the data, the fact that a satisfactory solution can be found with our model is already a major step toward understanding the geometry of and emissions from accreting neutron star pulsars.

Over the course of the outburst, we observed two types of transitions in the emission of EXO 2030+375: a transition in the pulse profiles and one in the hardness-luminosity relation. The spectral transition occurs, as is visible in Fig. 5, around $5.0 \times 10^{35} \text{ erg s}^{-1}$. The transition in the profiles appears to occur around a significantly higher luminosity of $1.7 \times 10^{36} \text{ erg s}^{-1}$. Assuming these to be signatures of one single state transition, it appears to manifest itself first in the spectrum before becoming apparent in the pulse profiles.

From these estimates of a critical luminosity, L_{crit} , we can derive a corresponding B -field estimate and compare this with existing claims. There are two theoretical derivations of L_{crit} ,

one analytical by [Becker et al. \(2012\)](#) and one numerical by [Mushtukov et al. \(2015b\)](#), both of which we want to apply for this purpose. Their assumptions differ in that [Becker et al. \(2012\)](#) equates the critical luminosity with the Eddington luminosity, while [Mushtukov et al. \(2015b\)](#) requires the matter to come to rest at the surface. Further, [Becker et al. \(2012\)](#) approximates the cross section by assuming photon energies below the cyclotron energies, while [Mushtukov et al. \(2015b\)](#) considers the effects of cyclotron resonance. The assumptions on the dominance of wind- or disk-accretion and the assumed spectral shape differ between the two works. For further details, consult the respective publications.

[Becker et al. \(2012\)](#) derives the critical luminosity as

$$1.5 \times 10^{37} B_{12}^{16/15} \text{ erg s}^{-1}, \quad (1)$$

while [Mushtukov et al. \(2015b\)](#) present a numerical solution in their Fig. 7. They derived L_{crit} for the two cases of purely extraordinary, polarization and an equal fraction of ordinary and extraordinary polarization, with the reality mostly likely lying in-between.

Theoretical models usually calculate the full bolometric X-ray luminosity in the rest frame of the neutron star surface. In order to compare our measured luminosities with theory, we therefore fit an extended model, including a cut-off power law to the two NuSTAR observations and their corresponding NICER data. For these, the 0.1–100 keV flux is 2.74 and 2.79 times higher than the flux in the 2–10 keV range. Therefore, we can multiply the previously stated observed transition luminosity by the average value of $2.75 \times (1+z)^2$, also accounting for the gravitational redshift of $z = 0.3$. This leads to a critical bolometric luminosity in the neutron star rest frame of $2.3 \times 10^{36} \text{ erg s}^{-1}$ for the spectral transition and $7.9 \times 10^{36} \text{ erg s}^{-1}$ for the transition seen in the pulse profiles.

Using these as a range for L_{crit} we can derive a surface magnetic field of 0.17–0.55 B_{12} for the model by [Becker et al. \(2012\)](#). According to [Mushtukov et al. \(2015b\)](#), a low L_{crit} can only be reached with mixed polarization and a surface B -field around $0.9\text{--}1.7 \times B_{12}$, while an L_{crit} close to $7.9 \times 10^{36} \text{ erg s}^{-1}$ would exclude this B -field range. Therefore, without further assumptions of the locally dominant polarization mode, no further restriction on the B -field strength can be made⁶.

As this work focuses on the monitoring data obtained by NICER, a very similar analysis of the Type II outburst of 2021 was performed by [Fu et al. \(2023\)](#) based on Insight, instead of NICER data. They also provide several estimates of the magnetic field strength of EXO 2030+375. First, by determining the critical luminosity from the pulse profile transition and, secondly, by applying the torque model by ([Ghosh & Lamb 1979](#)). [Fu et al. \(2023\)](#), however, use distances of 3.6 kpc and 7.1 kpc in their analysis. As argued in Appendix B, we judge the updated distance of 2.4 kpc as more reliable and therefore have to convert their reported values. The first method leads to a critical flux of $F_{\text{crit}}^{B12} \sim 1.1 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$, or $L_{\text{crit}}^{B12} \sim 1.7 \times 10^{37} \text{ erg s}^{-1}$ for a distance of 2.4 kpc and after correcting for gravitational redshift. This value is slightly higher than the critical luminosity determined similarly from the NICER data, probably due to the different energy range used. From this a B -field of $\sim 0.5 \times 10^{12} \text{ G}$ can be derived following [Becker et al. \(2012\)](#).

Alternatively, [Fu et al. \(2023\)](#) derived a B -field strength through torque modeling. To that end, they fitted the proportionality constant between the spin-frequency derivative $\dot{f}$ and $F^{6/7}$, where F is the source flux, measured by Insight. This constant can be compared with an expression depending on the B -field strength and the distance D , derived from the theory of [Ghosh & Lamb \(1979\)](#). In this way [Fu et al. \(2023\)](#) arrived at their Eq. (7), deriving the B -field strength as a linear function of D^{-6} . They used this relation to estimate a B -field strength of $\sim 0.41 \times 10^{12} \text{ G}$ and $\sim 24 \times 10^{12} \text{ G}$ for a distance of 7.1 kpc and 3.6 kpc, respectively. We can apply the same equation to the distance of 2.4 kpc, as generally assumed in our work, leading to a B -field strength of $\sim 270 \times 10^{12} \text{ G}$. This exceedingly high value is due to the strong D^{-6} dependence of the magnetic field strength. However, it is unclear whether, in the fit of [Fu et al. \(2023\)](#), relativistic corrections were applied to calculate the intrinsic luminosity in the neutron star rest frame. From Eq. (5) in [Fu et al. \(2023\)](#) one can see that $B \propto L^{-3}$. As the intrinsic luminosity is higher by a factor of $(1+z)^2$, this correction alone leads to a magnetic field strength that is ~ 5 times lower. Similarity, any over- or underestimation of the intrinsic luminosity due to beaming effects, which can be on the order of a factor 4–10 ([Falkner 2018](#)), will have strong effects on the derived magnetic field strength.

[Fu et al. \(2023\)](#) further point out that torque modeling and the critical luminosity sample the magnetic field at different radii from the neutron star and a deviation can be seen as a sign of a multipolar magnetic field. However, it should be noted that since [Ghosh & Lamb \(1979\)](#) there have been more approaches toward torque modeling with varying assumptions on the disk-magnetosphere interaction, which does have an effect on the estimated magnetic field (see, e.g., [Wang 1995](#); [Dai & Li 2006](#); [Rappaport et al. 2004](#)). Together, these effects lead to very large systematic uncertainties on the B -field estimates by [Fu et al. \(2023\)](#), which prevents us from claiming that these values would contradict each other.

Finally, we note the significantly lower peak luminosity reached during this latest outburst compared to the two previously observed Type II outbursts ([Epili et al. 2017](#); [Klochkov et al. 2008](#)). This might correlate with the earlier onset of the outburst than predicted by [Laplace et al. \(2017\)](#), leading to a potentially less saturated Be-decretion disk.

In summary, using both NICER and NuSTAR data covering the third detected giant outburst of EXO 2030+375, we investigated its changing spectral and timing behavior over the course of the outburst. We detected the familiar softening of the spectrum with increasing luminosity that fits well with previous outbursts ([Parmar et al. 1989a](#); [Reig & Nespoli 2013](#)). We described the pulse profiles through phenomenological fits to quantify the observed changes in the profile and successfully applied a physical light bending model to the profiles at high and low accretion rates. The multiple peaks and dips of the profile can be described simply as a result of a two-component (wall and top) emission pattern originating from two accretion columns. No further components from a more complex accretion geometry or absorption features are required. To further constrain the geometry with this approach, we would need to sample the entire parameter space and determine the uniqueness of the solution found. Methods such as nested sampling would provide a possible way to achieve this, but are beyond the scope of this paper.

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⁶ IXPE observations presented by [Malacaria et al. \(2023\)](#) do not provide a reliable estimate of the dominant polarization mode due to uncertainties in the B -field geometry and poorly understood effects of the “vacuum resonance”, by which photons can change polarization mode during propagation through the magnetosphere.

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Appendix A: Column emission model

One of the proposed mechanisms that form characteristic pulse profiles (PP) of accreting neutron stars is the formation of accretion columns at the magnetic poles. These columns are believed to form due to an accretion shock (Becker et al. 2012) and result in a cone-like structure that potentially emits photons from its walls and cap. To model phase-dependent emission we propose a simplified model for this emitting surfaces based on the work of Falkner (2018).

A.1. Solution to emitting surfaces problem in Schwarzschild metric

To calculate the total flux as seen by an observer, it is necessary to determine the visible surface of the emitting surface elements taking any blocking surface into account. Falkner (2018) proposed an approximation by describing the NS surface and column surface by a mesh grid and project any of the mesh vertices into the observer sky taking into account photon trajectory solutions of the Schwarzschild metric (Misner et al. 1973). The visible surface of the columns is then given by all surface elements that are not behind any other surface element. This is a computational effort and is simplified by considering the centroid of any given surface element only. If this centroid is within the (projected) boundaries of another surface element in front of it, it is deemed not visible.

Additional edge cases are taken into account as described in Falkner (2018).

For simplicity, we approximate the column structure as a cylinder that emits from the wall with surface $A_{\text{wall}} = \pi\rho h$, with the column radius ρ and column height h , and from the cap with emitting surface $A_{\text{cap}} = 2\pi\rho^2$. Each surface is divided into a fine grid of surface elements where each element is assumed to emit with an intensity in a given direction according to a Gaussian distribution centered around the surface normal. For the emission from the cap, we additionally allow for an offset from the surface normal such that we can account for potential suppression of the cap emission due to infalling matter.

A.2. Table model interpolation

The pulse profile is modeled assuming a NS with canonical mass $M = 1.4 M_{\odot}$ and radius $R = 10^6$ cm. Considering a (distorted) dipolar field, we place two emission columns on the surface with the location given by the angular displacement Θ from the rotation axis and a phase shift $d\phi$ relative to the line of sight direction (such that $d\phi = 0$ deg corresponds to the column being in the direction of the observer). The NS orientation is given by the inclination of the rotation axis i . For $i = 0$ deg the rotation axis points toward the observer. All parameters for one column are summarized in Table A.1.

Placing two columns on the NS surface, we want to find the total emission reaching the observer for any given rotational phase ϕ . Due to the computational effort, using the described method directly as a model is tedious. Instead, one can calculate an interpolation table for all parameters. While this is certainly possible, it has the disadvantage that at least 19 parameters are necessary, resulting in large tables and also slow interpolation. Additionally, if one wants to change the emission profiles, recalculation of the tables is required.

Instead, we can improve the interpolation model drastically under the following assumptions:

- Emission of one column is not blocked by the other.

Table A.1. Summary of model parameter

Parameter	Range	Description
column		
θ	0–180°	Angular distance of magnetic pole to rotation axis
i	0–180°	Inclination of rotation axis to observer direction
h	1–5 000 m	Height of accretion column
ρ	1–1 000 m	Radius of accretion column
$d\phi$	0–360°	Phase shift (relocates points where pole is in plane of rotation axis and observer direction)
wall/cap		
N	0– ∞	Total flux
μ	0–90°	Direction of principle emission (only for cap)
σ	10^{-6} – ∞	Width of emission beam

- Emission profile of all surface elements of cap and wall, respectively of one column are the same.
- Emission profiles of the surface elements are radially symmetric (with respect to the surface normal).
- Columns are radially symmetric around the $\Theta, d\phi$ direction.
- Time delay effects are negligible.

With this, to calculate the total flux for a given rotational phase it suffices to know the total visible surface $A(\gamma)$ observed under a certain angle γ for the cap and wall of a column separately. Given this information one can integrate over the product of emission function f and surface A for all angles to get the total emission

$$F = \int_0^{\pi/2} d\gamma f_{\text{wall}}(\gamma; \bar{\lambda}) A_{\text{wall}}(\gamma; h, \rho, \Theta) + f_{\text{cap}}(\gamma; \bar{\lambda}) A_{\text{cap}}(\gamma; h, \rho, \Theta). \quad (\text{A.1})$$

Here, $\bar{\lambda}$ are additional parameters for the emission profile f . As before we calculate a table model, now for A_{wall} and A_{cap} where only three parameters are required. Due to symmetry it suffices to consider only one angular displacement parameter (here Θ), arbitrary orientations are obtained by rotation. With this, not only the resulting table is much smaller, but also the total number of calculations necessary to populate the table are reduced such that changing the model is less time consuming.

A.3. Fancil model

With the previously described strategy we rebuild the fancil model (Falkner 2018; Iwakiri et al. 2019) where f is a Gaussian distribution, centered around $\gamma = 0$ rad for the wall emission, and centered around $\gamma = \mu$ for the cap emission. A large width of the Gaussian distribution corresponds to isotropic emission from each element.

To implement the fancil model we make use of the programmatic access of the internal data and fitting process in *ISIS* (Houck & Denicola 2000). Here we define two functions `wall` and `cap` which implement the emission profile. Due to the made assumptions these profiles are functions of one variable only and can in principle be replaced with other potential patterns. A third function `column` takes the output of the previous two functions, interpolates the calculated table and performs the integration for

all observed rotational phases. The result is the pulse profile for the given set of parameters.

A.4. Limitations

It is clear that due to the made assumptions the model is severely limited in some ways. The potential largest impact comes from the assumed radial symmetry of emission. It is known (Kraus et al. 1996) that emission from the wall is boosted toward the surface, hence, not symmetric. Further, the assumption of symmetry around the magnetic axis (Θ direction) is likely not reflecting the physical reality. Due to the fast rotation of the magnetic axis it is reasonable to believe that the accretion column is not symmetric around this axis. With this approach it is in principle possible to model more complicated multipole configurations by adding more columns. However, this results in columns being close to each other such that the shadowing between the columns can no longer be neglected. For this case it is necessary to solve the full problem which requires better algorithms to be applied as a fitting model. Besides the geometric effects we ignore any time dilation effects resulting in the reddening of emitting spectra. It is in principle possible to use the column function to predict phase-dependent spectra, but energy shifting effects need to be considered separately.

Appendix B: Distance to EXO 2030+375

Many of the astrophysical implications of observed state transitions depend on the luminosity at which the transition occurs, and therefore we have to establish the distance toward EXO 2030+375. Previous distance measurements were derived from modeling the spin-up during Type II outbursts (Parmar et al. 1989a; Reynolds et al. 1996), optical extinction (Wilson et al. 2002; Coleiro & Chaty 2013), and from direct Gaia parallax measurements (Gaia Collaboration 2016, 2018) as derived by Bailer-Jones et al. (2021). See Fig. B.1 for an overview of how the different methods yielded different distance estimates over time. Historically, a distance of 7.1 kpc has been used by most publications since Wilson et al. (2002). As also discussed by Coleiro & Chaty (2013), Wilson et al. (2002) assumed that the extinction in the Galactic plane is representative for the optical extinction toward EXO 2030+375. Using a more careful approach that takes into account multiple magnitude measurements in different opti-

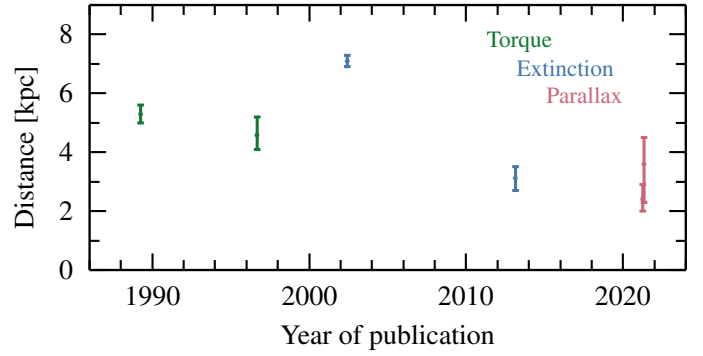


Fig. B.1. Literature distances toward EXO 2030+375. Included are Parmar et al. (1989a), Reynolds et al. (1996), Wilson et al. (2002), Coleiro & Chaty (2013), Bailer-Jones et al. (2021), Arnason et al. (2021), each colored by the technique used to determine the distance.

cal bands to fit both extinction and distance, Coleiro & Chaty (2013) therefore revised the extinction-based distance down to 3.1 ± 0.4 kpc.

This distance is consistent with direct parallax measurements from Gaia DR2 data, $3.6^{+0.9}_{-1.3}$ kpc (Arnason et al. 2021), which in the more recent early EDR3 data release has been revised to $2.4^{+0.5}_{-0.4}$ kpc (Bailer-Jones et al. 2021). As the latter includes the most recent Gaia data, equivalent to DR3 (Gaia Collaboration 2023), we judge this distance as most reliable and will use it in this paper to calculate luminosities, if not stated otherwise. As a consistency check, for each distance in the literature, we determine the absolute magnitude of the optical companion calculated from de-reddened Gaia G-band magnitudes. We find that the distance of 2.4 kpc results in a more realistic $M_V = -0.98$ mag for a B star, compared to $M_V = 1.52$ mag for 7.1 kpc. It should be noted that outside of the results presented here, the newer, lower Gaia distance also has significant implications for the interpretation of low luminosity observations, such as the detection of pulsations described by Füst et al. (2017). Recently Fu et al. (2023), very similar to our work, used *Insight*-HXMT monitoring of the 2021 outburst to constrain the critical luminosity from a transition point in the pulse profiles and from that estimate the B-field. However, Fu et al. (2023) only consider distances of 7.1 kpc (Wilson et al. 2002) and 3.6 kpc (Arnason et al. 2021), leading them to estimate higher luminosities compared to this work.