LETTER TO THE EDITOR

X-ray view of a merging supermassive black hole binary candidate SDSS J1430+2303: Results from the first ~200 days of observations

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Abstract

Context. Recently we discovered an unprecedented supermassive black hole binary (SMBHB) candidate in the nearby Seyfert galaxy SDSS J1430+2303, which is predicted to merge within three years. X-ray spectroscopy may bring unique kinematic evidence for the last inspiraling stage, when the binary is too close to allow each of them to hold an individual broad line region.

Aims. We try to confirm the unique SMBHB merger event and understand the associated high-energy processes from a comprehensive X-ray view.

Methods. We observed SDSS J1430+2303 with XMM-Newton, NuSTAR, Chandra, and Swift spanning the first ~200 days since its discovery.

Results. X-ray variability, up to a factor of 7, has been detected on a timescale of a few days. The broadband spectrum from 0.2–70 keV can be well fitted with a model consisting of a power law and a relativistic reflection covered by a warm absorber. The properties of the warm absorber changed dramatically, for example, with a decrease in the line-of-sight velocity from ~0.2c to ~0.02c, between the two XMM-Newton observations separated by only 19 days, which can be naturally understood in the context of the SMBHB; although, the clumpy wind scenario cannot be completely excluded. Broad Fe Kα emission has been robustly detected, though its velocity shift or profile change is not yet measurable. Further longer X-ray observations are highly encouraged to detect the expected orbital motion of the binary.

Keywords. galaxies: active – galaxies: nuclei – X-rays: galaxies – galaxies: individual: SDSS J1430+2303

1. Introduction

Supermassive black hole binaries (SMBHBs) are an inevitable and fascinating byproduct of galaxy mergers in the hierarchical Universe (Begelman et al. 1980) since most massive galaxies are expected to contain at least a central SMBH with a mass of $10^6$–$10^{10} M_\odot$ (Kormendy & Ho 2013). When two galaxies merge, the two SMBHs initially residing in the center of each galaxy sink to the common center of the merged system via dynamic friction. SMBHBs at this stage may be identified as dual active galactic nuclei (AGNs) with separations ranging from several parsecs to several kiloparsecs (e.g., Zhou et al. 2004; Liu et al. 2010; Comerford et al. 2015). As the two SMBHs continue to shrink by ejecting stars in a “loss cone”, they gradually become a gravitationally bound system on subparsec scales. Their orbital angular momentum is further lost due to some other mechanisms (e.g., Ivanov et al. 1999; Hayasaki 2009) until gravitational wave (GW) radiation takes over. The final coalescence of SMBHBs is thought to be the loudest GW sirens (Thorne & Braginskii 1976; Haehnelt 1994; Jaffe & Backer 2003), which are the primary targets of ongoing and upcoming GW experiments, such as of the Pulsar Timing Arrays (PTAs) and the Laser Interferometer Space Antenna (LISA).

In spite of the attractive prospects, close SMBHBs with separations below a parsec scale are however extremely challenging to unveil as they are far beyond the resolution limit of the current generation of telescopes, except for the very few nearby galaxies for which long baseline radio interferometry observations are possible (Gallimore & Beswick 2004).
The search of subparsec binaries thus must rely on some indirect measurements, such as the shift of broad emission lines due to its orbit motion (Eracleous et al. 2012; Shen et al. 2013; Runnoe et al. 2017), the presence of double-peaked emission profiles from the coexisting broad-line regions associated with individual accreting SMBHs (e.g., Boroson & Lauer 2009), or a drop in the UV continuum due to a gap opened by the secondary BH migrating within the circumbinary disk (Guilettin & Miller 2012; Yan et al. 2015). Another promising method is the periodic variations of AGNs, which reveals the possible presence of the SMBHB system in the blazar OJ 287 (Sillanpaa et al. 1988; Lehto & Valtonen 1996), and it has become particularly popular recently in virtue of modern time-domain surveys. The periodicity can also be understood as either accretion rate fluctuations (MacFadyen & Milosavljević 2008; Noble et al. 2012; Graham et al. 2015a) or relativistic Doppler modulation (D’Orazio et al. 2015), on a timescale comparable to the orbit period. Although a mounting number of candidates have been selected (e.g., Graham et al. 2015b; Liu et al. 2016; Charisi et al. 2016; Zheng et al. 2016; Chen et al. 2020), none of them are really approaching its final coalescence such that the observed periods stay constant in time.

Recently, we have discovered a possible candidate SMBHB close to the merger stage in a nearby galaxy SDSS J143016.0+230344.4 (hereafter SDSSJ1430+2303) at z = 0.08105 (Jiang et al. 2022). SDSSJ1430+2303 was initially noticed during our systematic search for mid-infrared (MIR) outbursts in nearby galaxies (MIRONG, Jiang et al. 2021). A careful check of its optical light curves from the Zwicky Transient Facility (ZTF) then revealed unique chirping flares, with a reduced period from about one year to only three months by the end of 2021. The flares can be ideally interpreted as emissions from plasma balls that are kicked out from the primary SMBH accretion disk by an inspiraling secondary SMBH during disk crossings. We have developed a trajectory model to explain the period evolution and predicted that the binary would merge within three years, making multiwavelength follow-up observations rather pressing and exciting. Since its discovery, we have triggered intensive follow-up observations in multi-wavelength regimes (e.g., An et al. 2022a,b). Among them, X-ray observations are essential for confirming the SMBHB scenario and understanding the associated high-energy physical processes happening during the last inspiraling stage. In particular, the binary is so compact that individual SMBHs are not allowed to possess their own broad line regions, but they can still have their own accretion disks. The orbital motion of SMBHs causes a unique velocity shift of the emission lines in the reflected light of the accretion disk or of the absorption lines from the accretion disk wind. If such signatures are detected, they provide independent kinematic evidence for the existence of the SMBHB. In this Letter, we report the X-ray results of SDSSJ1430+2303 observed with Swift, XMM-Newton, Chandra, and NuSTAR during the first ~200 days follow-ups since its discovery.

2. Observations and data reduction

2.1. Swift

In addition to the intriguing optical light curves, we also note four epochs of observations from the X-Ray Telescope (XRT) on the Neil Gehrels Swift observatory (Swift for short), including one targeted observation (ToO ID:13234, PI: López Navas) on 2018 November 24 and another three occasional visits in 2019 and 2020. The four snapshots give a count rate of 0.05–0.1 cts s$^{-1}$, corresponding to an X-ray luminosity of $(0.5–1) \times 10^{34}$ erg s$^{-1}$ in 0.3–10 keV, assuming a fixed average photon index ($\Gamma$ = 1.66). The high X-ray count rate allowed us to monitor its X-ray luminosity with reasonable time.

We note that when we discovered the chirping flares of SDSSJ1430+2303 in 2021 September, the target was however not visible by a ground telescope in night. We immediately triggered the X-ray monitoring program with Swift after the period of Sun constraint, when SDSSJ1430+2303 still remained unobservable for ground-based telescopes. As an exploratory observing experiment, we first initiated a one-month-long monitoring from 2021 November 23 to December 21 with a three-day cadence, and each observation has an exposure time of ~1 ks (PI: Jiang, ToO ID:16602). With the Swift observations, we found a large amplitude of X-ray variability (0.01–0.1 cts s$^{-1}$) with a seemingly even shorter period, which has decreased to only one month. Thus we chose to change the observing strategy to a daily cadence in the subsequent request after December 25. However, Swift science instruments went into safe mode because of an unexpected reaction wheel failure$^1$ between 2022 January 18 and February 18. We restarted the daily monitoring when Swift returned to science operations, which was then followed with a two-day cadence up to now.

We reprocessed the Swift/XRT observations following the standard data reduction using tools in HEASOFT (v.6.30) with the latest calibrations. The event files have been rebuilt by the task xrtpipeline, with only the observations operated in “photon counting” mode being used. We extracted source photons using a circular region with a radius of 47.2" centered on the target and background photons from an annulus region free of source emission. The net count rates in the 0.3–10 keV band for each observation were then calculated and the corresponding count rate light curve was constructed.

2.2. XMM-Newton

During the Swift daily monitoring, we also triggered two epochs of XMM-Newton DDT observations on 2021 December 31 and 2022 January 19, respectively (obsid: 0893810201 and 0893810401). We reprocessed the XMM-Newton/EPIC data with the Science Analysis Software (SAS, v.20) and the latest calibration files. Only the data from the pn instrument of EPIC were used for our analysis in view of its higher sensitivity than MOS instruments. We created the events files with the tool of epchain. After removing the “bad” pixels, we created the high flaring particle background time intervals with a threshold rate of >0.6 cts s$^{-1}$ with single events (“PATTERN=0”) in the 10–12 keV band. This resulted in a net exposure time of 36.06 and 40.54 ks for the two observations, respectively. We used only the single events for the science analysis. We extracted the source spectra from a circular region with a radius of 40" centered on its optical position, and the background spectra from a nearby source-free circular region with the same radius.

2.3. NuSTAR

A NuSTAR ToO observation was performed from 2022 February 3 to 6 with a total exposure time of 102.9 ks during an observation span of 212 ks. We reprocessed the NuSTAR data using the latest calibration files with the tools in HEASOFT. We used the task nupipeline to filter the event lists with the options of

$^1$ https://swift.gsfc.nasa.gov/news/2022/safe_mode.html
We note that SDSSJ1430+2.5. NICER of 57.4 ks. observations into one stacked spectrum, which resulted in variability within each observation. Finally, we merged all the sive analysis. The level 2 NICER event files were first repro-

we will also put them together for a light curve comprehen-

monitor since 2022 January 20 by NICER (Pasham et al. 2022),

After eliminating the high energy background time intervals, the 

rates of 0.12–0.23 cts s\(^{-1}\) in the 0.5–8 keV. We found no obvious variability within each observation. Finally, we merged all the Chandra observations into one stacked spectrum, which resulted in an average count rate of 0.16 cts s\(^{-1}\) with a total exposure time of 57.4 ks.

2.4. Chandra

We requested 15 Chandra DDT observations (PI: Jiang N.) which were performed from 2022 February 21 to March 16 with an average exposure time of 4 ks. We reprocessed the Chandra data with CIAO (v.4.14) and the latest calibration files (v.4.9.6). The level 2 event files were recreated by the script of chandra_repro. The spectra of source and background, as well as the response files, were produced by the script of specextract. The source photons were extracted from circular regions with a radius of 7″–25″ depending on the offset between the position of the source and the observation viewing center. Larger source extraction regions were selected because some Chandra observations were performed off-axis. The background was extracted from larger annulus source-free regions with the same source centers. This resulted in count rates of 0.12–0.23 cts s\(^{-1}\) in the 0.5–8 keV. We found no obvious variability within each observation. Finally, we merged all the Chandra observations into one stacked spectrum, which resulted in an average count rate of 0.16 cts s\(^{-1}\) with a total exposure time of 57.4 ks.

2.5. NICER

We note that SDSSJ1430+2303 has also been continuously mon-
tored since 2022 January 20 by NICER (Pasham et al. 2022), we will also put them together for a light curve comprehen-
sive analysis. The level 2 NICER event files were first repro-
duced following the standard processing by the task nicer12.

After eliminating the high energy background time intervals, the spectrum and light curve of each observation were extracted by the tool of xselect. We used the 3C50 model to estimate the NICER background by using the task n1backgen3C50 .pl. The background-subtracted count rate of each observation was in the range of 1.1–3.3 cts s\(^{-1}\) in 0.3–4 keV band.

3. X-ray light curves

In Fig. 1, we show the X-ray light curves of Swift/XRT observations in 0.3–10 keV, Chandra/ACIS-S observations in 0.5–

10 keV, and NICER observations in 0.3–4 keV. In order to compare the variability between different observations, we norm-
alized the count rates of the light curves from Chandra and NICER observations to the averaged count rate obtained from the Swift observations, that is to say from the quasi-simultaneous observations from 2022 February 21 to March 16.

Although NICER yielded a much higher count rate, and thus signal-to-noise ratio (S/N), than Swift/XRT due to its larger effective area, the lack of imaging ability yet a

large field of view of 28 arcmin\(^2\) (Arzoumanian et al. 2014) makes it difficult to mitigate the contamination of the nearby quasar SDSS J143008.64+230621.5 (SDSSJ1430+2306 here-after), which also falls into the field view of the target (about 3.1 arcmin offset). The quasar has a count rate about 1–200% of our target and is highly variable in the X-ray band as is illustrated in the Swift/XRT light curve in Fig. 1. Thus, we caution that special attention should be paid when analyzing the NICER light curve or spectrum independently.

We also generated the background-subtracted light curves for the two XMM-Newton observations after correcting for the detection efficiency effect with the tool epiclccorr. As shown in Fig. A.1, we have checked the light curves in the 0.2–0.5, 0.5–

1, 1–2, and 2–10 keV bands individually, and found no obvious variability on the hour timescale. The average net count rates in the 0.2–10 keV band are both around 1.2 cts s\(^{-1}\), though there was a slight rising trend from 1.1 to 1.3 cts s\(^{-1}\) during the first visit. Moreover, the power spectrum analysis did not detect any quasi-periodic oscillation signals with a high confidence.

4. X-ray spectral analysis

We checked the source and background spectra of the XMM-

Newton, stacked Chandra, and NuSTAR observations, and found that all the source spectra have enough S/N, except for the NuSTAR spectrum at energies above 35 keV, which is dominated by the background. We then regrouped the spectra to ensure there were at least 25 net counts per energy bin for using the \(\chi^2\) statistics in the spectral fittings with XSPEC. During the fittings, a neutral absorption column density was included and fixed to the Galactic value (“phabs” in XSPEC, \(N_\text{H} = 2.28 \times 10^{20} \text{cm}^{-2}\), HI4PI Collaboration 2016), and the uncertainties are given at a 90% confidence level for one parameter (\(\Delta \chi^2 = 2.706\), unless stated otherwise. We assumed a cosmology with \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\) in this work.

We first applied a simple Galactic absorbed power-law model to fit, jointly, the two XMM-Newton pn (marked as xmmobs1 and xmmobs2) in 2–5 and 8–10 keV, Chandra stacked spectra in 2–

5 keV, and the NuSTAR merged spectrum in 3–5 and 8–10 keV, while the power-law normalization of each spectrum was set as a free parameter. The fitting bands were chosen so as to miti-
gate a potential impact of disk reflection or warm absorption. We obtained photon indices of \(\Gamma = 1.65 \pm 0.07\), 1.61 \pm 0.07,
When applying the model to the broadband 3–70 keV spectrum of the NuSTAR observation and the 0.2–10 keV band spectra of the two XMM-Newton observations, we found a high-energy cut-off feature above 30 keV in the residual spectrum and apparent deficit features around 0.2–1 keV, as shown in the middle panel of Fig. 3. We then tried to perform joint fits to the broadband spectra of XMM-Newton in 0.2–10 keV band, the Chandra stacked spectrum in 0.5–8 keV, and NuSTAR spectra in the 3–70 keV band, with a relativistic reflection disk model modified by a warm absorber. For the warm absorber, we ran xstar2xspec to create a table grid model (“warmabs” in XSPEC, Kalman & Bautista 2001) by assuming a density of $n = 10^3 \, \text{cm}^{-3}$, photon index of $\Gamma = 1.7$, and $\nu_{\text{tur}} = 3000 \, \text{km s}^{-1}$. We fixed the intrinsic cosmological redshift of the warm absorber at 0.08105, that is the one measured from the optical spectrum (Jiang et al. 2022). As the NuSTAR spectrum does not extend to the lower energies (0.2–3 keV) and since the Chandra spectrum has a low S/N below 1.5 keV, we tied the absorber parameters, that is to say the hydrogen column density ($n_H$) and ionization parameter of $\log [\epsilon / \text{erg cm}^{-1}]$, in the NuSTAR and Chandra spectral fitting to the ones in xmmobs2. On the other hand, for the relativistic reflection (“relxill” in XSPEC, Garcia et al. 2014), we tied the model parameters to those used to fit the NuSTAR spectrum, as the XMM-Newton and Chandra observations lack data in the 10–79 keV band. There are still too many parameters to constrain, given the degeneracies, so we fixed the inner radius of $R_{\text{in}}$ at the marginally stable orbital radius for BH spin $a = 0.5$, the outer radius of $R_{\text{out}}$ at 400 $R_g$, and the power-law emissivity at $q = 3$ for the reflection model. The fitting result is acceptable ($\chi^2 / \text{d.o.f.} = 903.5 / 847$). When replacing the reflection component with a power-law component or removing the warm absorber, the fitting became much worse ($\chi^2 / \text{d.o.f.} = 1074.7 / 851$, or 1027.7 / 851).

We further checked for the model with a velocity shift in the absorber along our line of sight (with the convolution model “zmshift” in XSPEC). We found that the model with a shift absorber with a different velocity can further reduce $\Delta \chi^2 = 26.0$ for two extra d.o.f. We also found that the shift partial absorber (with the convolution model “partcov” in XSPEC) with a different velocity was not required. It can only further reduce $\Delta \chi^2 = 3.8$ for one extra d.o.f., with a partial covering factor of $f_c = 0.56^{+0.13}_{-0.18}$ for xmmobs1 and $f_c = 1$ for xmmobs2. However, we cannot exclude the partial covering scenario from the spectral fittings. We also checked other values of turbulent velocity $\nu_{\text{tur}}$ ranging from 100 to 10 000 km s$^{-1}$. The results are broadly consistent with the present ones. We listed all the fitting results from a median turbulent velocity value of 3000 km s$^{-1}$ in Table A.2.

Finally, we obtained a best-fit result with a shifting warm absorbed reflection model ($\chi^2 / \text{d.o.f.} = 877.5 / 845$). The X-ray spectra with the best-fit model are shown in Fig. 3. We found a reflection component with a power-law index for the incident spectrum of $\Gamma = 1.59^{+0.03}_{-0.02}$ a high-energy cut-off of $E_{\text{cut}} = 96.8^{+31.6}_{-23.1}$ keV, the ionization of the reflection disk of $\log [\epsilon / \text{erg cm}^{-1}] = 3.27^{+0.17}_{-0.17}$, an inclination angle of $i = 21^{+8}_{-11}$, and a reflection factor of $f_r = 0.49^{+0.44}_{-0.08}$. As the high-energy cut-off of $E_{\text{cut}}$ cannot be constrained well by the model and since the obtained value is consistent with those found in the Swift/BAT AGNs sample (Ricci et al. 2017), we further fixed the $E_{\text{cut}}$ at 100 keV.

We note that the warm absorber with an H column density and ionization parameter of $n_H \sim 7.6 \times 10^{20} \, \text{cm}^{-2}$ and $\log [\epsilon / \text{erg cm}^{-1}] \sim 0.8$ is required for xmmobs1. In xmmobs2, the H column density and ionization parameter of the warm absorber are found to be $n_H \sim 3.8 \times 10^{23} \, \text{cm}^{-2}$ and $\log [\epsilon / \text{erg cm}^{-1}] \sim 0.8$.

Fig. 2. Two XMM-Newton/NuSTAR spectra in 2–10 keV with a simple power-law model, and the ratio of the data and model. Upper panel: model was fitted for the 2–5 and 8–10 keV band spectra and extrapolated to 2–10 keV. Middle panel: ratio of the data and model with the simple power-law model, and obvious excess in the 5–8 keV band of the two XMM-Newton/NuSTAR observations. Bottom panel: ratio of the data and model with the simple power-law plus a Gaussian line model, which might be a relativistic broadening Fe K emission.

$1.65 \pm 0.10, 1.71 \pm 0.07$ for xmmobs1, xmmobs2, Chandra, and NuSTAR spectra, respectively, with a total $\chi^2 = 373.6$ for 347 degree of freedom (d.o.f.). The indices are consistent with each other within uncertainties in spite of a tentative softer-when-brighter trend. If bounding their photon indices together, we obtained an index of $1.66 \pm 0.04$, which only increased the total $\Delta \chi^2 = 2.6$ for the decrease of three d.o.f. The results from the joint fitting were adopted by us, giving observed 2–10 keV fluxes of $2.85 \pm 0.05 \times 10^{-12}$, $2.62 \pm 0.05 \times 10^{-12}$, $2.51 \pm 0.05 \times 10^{-12}$, $3.72 \pm 0.04 \times 10^{-12}$ erg cm$^{-2}$ cm$^{-2}$ for xmmobs1, xmmobs2, Chandra, and NuSTAR observations, respectively. Albeit with a large amplitude in variability, the two XMM-Newton epochs were unfortunately observed at almost identical flux levels while the NuSTAR observation was performed at a stage with a flux 30–40% higher. These results are consistent with a constant spectral index for observations.

However, as shown in the residual spectrum (see the middle panel of Fig. 2), obvious excesses in the 5–8 keV band are visible in the two XMM-Newton/NuSTAR and Chandra observations after the power-law model was interpolated to the above region. We then added a Gaussian line to the model, which yielded a total $\chi^2 = 560.3$ for 538 d.o.f., with $\Delta \chi^2 = 25.0$ for the addition of six d.o.f. The addition of a Gaussian line model improved the fits significantly, with a confidence level of 99.96% as determined through 10 000 Monte Carlo simulations using the XSPEC script simfitest (see also Protassov et al. 2002). The fitted Gaussian line is peaked at $E = 6.55^{+0.32}_{-0.31}$ keV with a width of $\sigma = 0.69^{+0.15}_{-0.12}$ keV. If the line center and width are fixed to the best value, the line detection confidence is 99.1%, 99.5%, and 99.3% for the xmmobs1, xmmobs2, and Chandra observation, respectively. However, the detection confidence for the independent NuSTAR spectral fitting is much lower, that is to say 65%, indicating that the line is weak or not detected. The equivalent width of the Gaussian broad line is 0.22, 0.30, and 0.37 keV for the xmmobs1, xmmobs2, and Chandra observation, respectively, which is tentatively anticorrelated with the continuum flux, while the parameters of the line normalization are consistent with each other, if considering the uncertainties. Such a broad Gaussian line component can be naturally treated as a relativistic broadened Fe K$\alpha$ emission line around 6.4 keV (e.g., Nandra et al. 2007).
log \([\xi_\text{w}/(\text{erg cm s}^{-1})]\) \sim 1.9, respectively. Interestingly, an ultra-fast outflowing velocity of \(0.193^{+0.014}_{-0.021}\) is found for xmmobs1, but the outflowing velocity decreases to \~0.021c for xmmobs2. This suggests that the warm absorber has dramatic variations in the column density, ionization parameter, and outflowing velocity, though the X-ray continuum flux has only changed by \sim 10%.

5. Summary and discussion

We present an analysis of the X-ray observations of the unprecedented SMBH binary candidate predicted to merge within three years in a nearby galaxy SDSSJ1430+2303, covering a period from 2021 November 23 to 2022 June 4 by Swift, XMM-Newton, Chandra, and NuSTAR. Dramatic variability was found in the X-ray light curve spanning \~200 days. No significant X-ray variability on short timescales of a few hours or shorter was found, as suggested by the two XMM-Newton observations. The detailed joint analysis of the high-quality X-ray spectra taken by XMM-Newton (50 and 75 ks), NuSTAR (100 ks), and Chandra (57.6 ks) revealed notable spectral features including a warm absorber, broad Fe K emission, and a high-energy cut-off. We finally adopted a warm absorbed relativistic reflection model to describe the broadband X-ray spectra in the 0.2–70 keV band.

Both the obtained photon index (\(\Gamma \sim 1.6\)) and high-energy cut-off (\(E_{\text{cut}} \sim 100\) keV) of the reflection component are similar to those of other X-ray bright AGNs. The reflection factor (\(f_r \sim 0.5\)) and ionization (log \([\xi_\text{w}]\) \sim 3.2) also agree well with that given by Pasham et al. (2022) from a preliminary analysis of the NICER and NuSTAR data. These results strongly indicate an accretion disk origin for the reflection. Moreover, the low inclination angle (\(i \sim 20^\circ\)) implies that the accretion disk is approximately viewed face-on. This is consistent with the VLBI observations (An et al. 2022b) in which a single compact core is detected, and is also consistent with the type 1 AGN classification of SDSSJ1430+2303, even though it was initially discovered by nuclear MIR outbursts (Jiang et al. 2021).

For the warm absorber, we found clear variability in the column density, ionization parameter, and outflowing velocity between the two XMM-Newton observations (see Fig. 4) within only \~19 days. In particular, the outflowing velocity has changed from \~0.193c to \~0.021c, accompanied by a change in the ionization parameter log \([\xi_\text{w}/(\text{erg cm s}^{-1})]\) from 0.8 to 1.92. This is somewhat surprising since the variability in the X-ray continuum flux is marginal (it changed by only \sim 10%).

The outflowing, even ultra-fast (\(v > 0.1c\)) outflowing warm absorber has been widely found in X-ray luminous AGNs. Winter et al. (2012) detected a warm absorber in about half of a sample of 48 Seyfert galaxies. Tombesi et al. (2013) suggest that the ultra-fast outflowing absorber is present in about 35% of nearby Seyfert galaxies. Such an outflow or ultra-fast outflow is usually interpreted as due to the wind clumps being ejected with different velocities, inclinations, or launching radii from the accretion disk. The physical mechanisms driving the wind could be associated with radiation pressure and/or a magnetic field. Interestingly, the warm absorber in SDSSJ1430+2303 displays a lower ionization parameter at a higher outflowing velocity. Such a phenomenon has rarely been seen alone in previous studies of AGNs (e.g., Tombesi et al. 2013; Laha et al. 2014). A low-ionized-high-velocity outflow accompanying a high-ionized-high-velocity outflow was only detected in a few AGNs, such as IRAS 17020+4544 (Longinotti et al. 2015) and...
PG 1114+445 (Serafinelli et al. 2019). Even though the possibility of clumpy disk wind in typical AGNs cannot be completely excluded, the phenomenon in SDSSJ1430+2303 is inconsistent with the predictions from radiation-driven or magnetohydrodynamic-driven winds \(v_{\text{out}} \propto \xi^{0.5}\) or \(v_{\text{out}} \propto \xi\). King (2003; Fukunura et al. 2010). However, the abnormality is not difficult to understand in the SMBHB scenario, that is to say the observed high-velocity outflowing gas could be simply associated with either the orbital motion of the secondary SMBH or the gas that is kicked out during the disk crossing. It would thus be worthwhile to further characterize the temporal variations of the warm absorber.

Lastly, the broad Fe Kα emission is detected at a confidence level of 99.96% in both Chandra and XMM-Newton observations. The equivalent width of the broad Fe Kα emission is found in the range of \(\sim 190–320\) eV. Including the data from simultaneous NuSTAR observations, the broad X-ray spectra in the 0.2–70 keV can be self-consistently described by a relativistic reflection model. However, the potential velocity shift or profile changes of the broad Fe Kα emission, which can be considered as the smoking-gun evidence for the SMBHB binary scenario, cannot be measured between the two XMM-Newton observations due to the poor spectral quality. We still encourage further experiments with deeper X-ray observations, particularly at the phase with lower continuum levels. X-rays appear to be the most powerful probe to test the SMBHB interpretation or other proposals (Dotti et al. 2022), especially in the anticipated final inspiraling stage until the GW memory signal is detected.

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Appendix A: Additional tables and figures

Table A.1. Power-law fitting result for the spectra in 2–5 keV of two XMM-Newton and Chandra, 3–5 keV of NuSTAR, and 8–10 keV of two XMM-Newton and NuSTAR observations.

| Observations       | \( \Gamma \) | \( \chi^2/d.o.f. \) |
|--------------------|--------------|----------------------|
| XMM-obs1           | 1.65 ± 0.07  | 2.85                 |
| XMM-obs2           | 1.61 ± 0.07  | 2.62                 |
| Chandra            | 1.65 ± 0.10  | 2.51                 |
| NuSTAR             | 1.71 ± 0.07  | 3.72                 |

|                | \( F_{2-10\text{keV}} \) | \( L_{2-10\text{keV}} \) |
|----------------|--------------------------|--------------------------|
| XMM-obs1       | 4.75 × 10^{30} erg cm\(^{-2}\) s\(^{-1}\) | 4.53 × 10^{33} erg s\(^{-1}\) |
| XMM-obs2       | 4.75 × 10^{30} erg cm\(^{-2}\) s\(^{-1}\) | 4.53 × 10^{33} erg s\(^{-1}\) |
| Chandra        | 4.75 × 10^{30} erg cm\(^{-2}\) s\(^{-1}\) | 4.53 × 10^{33} erg s\(^{-1}\) |
| NuSTAR         | 4.75 × 10^{30} erg cm\(^{-2}\) s\(^{-1}\) | 4.53 × 10^{33} erg s\(^{-1}\) |

Jointly fitting:

- \( \chi^2/d.o.f. = 1.66 ± 0.04 \)

\[ \chi^2/d.o.f. = 3.76/2.350 \]

Table A.2. Warm absorbed reflection modeling result.

| Observations       | zmshift | \( n_H \) | \( \log [\xi_c] \) | \( \log [f_c] \) | \( \Gamma \) | \( \log [f_{\text{relxill}}] \) | \( f_r \) | \( i_{\text{incl}} \) | \( \chi^2/d.o.f. \) |
|--------------------|---------|----------|----------------|----------------|---------|----------------|----------|----------------|----------------------|
| XMM-obs1           | 0       | 1.07±0.13 | 1.25±0.40 | 3.31±0.05 | 1.56±0.03 | 79.9±11.3 | 0.60±0.16 | < 21         | 903.5/847           |
| XMM-obs2+C+N       | 0.02+0.01 | 2.05±0.43 | 1.48±0.37 | 3.30±0.10 | 1.58±0.03 | 95.0±25.0 | 0.50±0.13 | 19+8         | 893.5/846           |
| XMM-obs1           | −0.03±0.01 | 3.24±0.18 | 1.92±0.06 | 3.40±0.13 | 1.59±0.04 | 96.8±23.7 | 0.49±0.04 | 25+8         | 877.5/845           |
| XMM-obs2+C+N       | −0.02±0.01 | 3.81±0.06 | 1.92±0.08 | 3.72±0.13 | 1.59±0.02 | 100        | 0.49±0.08 | 25+8         | 877.5/846           |
| XMM-obs1           | −0.02±0.01 | 4.32±0.03 | 1.92±0.08 | 3.72±0.13 | 1.59±0.02 | 100        | 0.49±0.08 | 25+8         | 877.5/846           |
| XMM-obs2+C+N       | −0.02±0.01 | 4.32±0.03 | 1.92±0.08 | 3.72±0.13 | 1.59±0.02 | 100        | 0.49±0.08 | 25+8         | 877.5/846           |
| XMM-obs1           | −0.02±0.01 | 4.32±0.03 | 1.92±0.08 | 3.72±0.13 | 1.59±0.02 | 100        | 0.49±0.08 | 25+8         | 877.5/846           |
| XMM-obs2+C+N       | −0.02±0.01 | 4.32±0.03 | 1.92±0.08 | 3.72±0.13 | 1.59±0.02 | 100        | 0.49±0.08 | 25+8         | 877.5/846           |

Fig. A.1. X-ray light curves of the two XMM-Newton/pn observations with a time bin size of 300 s in each 0.2–0.5, 0.5–1, 1–2, and 2–10 keV band. Left panel: observation on 2021 December 31 (xmmobs1). Right panel: observation on 2022 January 19 (xmmobs2).