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Study on the One-year Accuracy of Pulsar Timescale (Postprint)

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Abstract

Determining accurate pulsar timing model parameters is essential for establishing TT(PT), a realization of Terrestrial Time (TT) based on a pulsar timescale (PT). This study discusses the impact of different data spans on the accuracy of pulsar timing model parameters when determining pulsar timing model parameters. Using observations of PSR J0437-4715, J1909-3744, J1713+0747, and J1744-1134 from the second data release of the International Pulsar Timing Array (IPTA II, Version A), we compare the accuracy of the timing model parameters determined by these observations with different data spans. The results show for PSR J0437-4715, J1713+0747, and J1909-3744, the amplitude fluctuations of rotational frequency remain within 10−15, 10−14, and 10−14 Hz, respectively, when the data spans for determining pulsar timing model parameters exceed 13, 14, and 6 yr. Additionally, the one-year accuracy of TT(PT) is crucial for its application in timekeeping. By comparing the frequency deviations of TT(PT) relative to TT(BIPM) under both ideal (kr) and actual (kp) conditions across different data spans, we find that when the data span reaches the duration above, the accuracy of TT(PT) surpasses that of TT(TAI) under ideal conditions, slightly inferior under actual conditions. This suggests with improved observational technologies, the accuracy of TT(PT) can be further enhanced.

Full Text

Preamble

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A Multi-faceted View of the X-Ray Spectral Variability in Seyfert Galaxy Ark 120

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Abstract

We present a comprehensive study of the complex X-ray spectral variability in the Seyfert 1 galaxy Ark 120, utilizing multiple analytical techniques including multi-band light curves, softness ratio analysis, structure functions, rms spectra, cross-correlation functions, and spectral ratios from different time intervals. Our analysis is based on a re-examination of six XMM-Newton observations taken between 2003 and 2014. We find a clear "softer-when-brighter" trend in the 2–10 keV power-law component over long timescales, though this trend is timescale-dependent and much weaker on shorter timescales, similar to previous detections in NGC 4051. Notably, we observe a rare "harder-when-brighter" trend during one exposure, indicating dynamic changes in the spectral variability behavior of the power-law component. This exceptional exposure shows spectral variability characterized by power-law pivoting at an unusually low energy of ~2 keV, suggesting intricate variations in the thermal Comptonization processes within the corona. Furthermore, when data below 2 keV are included, we find that the soft excess component adds significant complexity to the spectral variability, as evidenced by a transition from "harder-when-brighter" to "softer-when-brighter" during another single exposure. This additional complexity arises because the variability of the soft excess sometimes follows and sometimes does not follow the changes in the power-law component. Our findings underscore the necessity of applying multiple analytic techniques to fully capture the multifaceted spectral variability of AGNs.

Key words: galaxies: active – galaxies: Seyfert – X-rays: galaxies

1. Introduction

Active galactic nuclei (AGNs), the dominant X-ray emitters in the extragalactic sky, are among the most luminous and variable sources in the universe, powered by accretion onto supermassive black holes (SMBHs) at their centers. The primary X-ray emission in AGNs—characterized by a power-law spectrum with a high-energy cutoff (Zdziarski 1995; Ricci 2011; Tortosa 2018; Kang 2020; Kang 2022)—is widely believed to originate from inverse Compton scattering of optical and ultraviolet seed photons from the accretion disk by high-energy electrons in a compact, hot corona near the SMBH (Galeev 1979; Haardt 1991; Haardt 1993). However, the physical nature of the corona remains poorly understood.

X-ray spectral variability in AGNs can provide essential insights into the nature of the X-ray corona and the mechanisms driving the observed variability. A prominent feature of X-ray spectral variability is the "softer-when-brighter" behavior generally seen in AGNs with intermediate to high Eddington ratios, where the power-law spectrum steepens as the X-ray flux increases (Markowitz 2004; Sobolewska 2009; Soldi 2014). Although it has long been suspected that the corona could cool when the X-ray flux increases, resulting in a softer spectrum, the underlying mechanisms remain poorly understood. This is particularly puzzling given that coronal temperature generally tends to increase with X-ray flux (Keek 2016; Zhang 2018; Kang 2021; Pal 2023), though opposite examples exist (Barua 2020; Masterson 2022; Wilkins 2022). Such temperature increases would conversely produce harder spectra at higher fluxes if the coronal geometry and opacity remained unchanged. Therefore, non-static scenarios such as jet-like flaring coronae (Wilkins 2015; Alston 2020) or outflowing coronae (Liu 2014) must be involved. Meanwhile, some AGNs show insignificant "softer-when-brighter" behavior or even "harder-when-brighter" trends (mostly at low Eddington ratios), suggesting different origins for their X-ray emission or variability (Emmanoulopoulos 2012; Connolly 2016).

Remarkably, Wu (2020) revealed that an empirical "softer-when-brighter" trend is insufficient to explain the observed spectral variability in NGC 4051, a Seyfert galaxy with an Eddington ratio of ~0.2 (Yuan 2021), and demonstrated that this behavior is timescale-dependent. The spectral variability track for a single source may also vary between observations (Sarma 2015). These facts further demonstrate the complexity of the underlying physical processes.

In addition to the power-law continuum, a soft X-ray excess—significant surplus emission in the soft X-ray (< 2 keV) range—has been observed in many sources (Arnaud 1985; Gierlinski 2004; Piconcelli 2005; Crummy 2006; Bianchi 2009). The nature of this soft excess remains unclear, with two leading theories: Comptonized emission from an extra "warm corona" (Done 2012; Petrucci 2013), or relativistically blurred reflection from the inner accretion disk irradiated by the hot corona (Ross 1993; Crummy 2006). The soft excess component can significantly affect the observed X-ray spectral variability and must therefore be considered in variability analyses. Indeed, spectral variability can be used to probe the origin of the soft excess (Mehdipour 2011; Ponti 2012; Jin 2013; Jin 2021; Nandi 2021).

Various approaches exist to reveal X-ray spectral variability. Directly comparing spectra from different epochs is the most straightforward method. However, for rapid spectral variability within individual exposures, the hardness ratio (or softness ratio) is generally adopted to quantify the spectral slope and plot it against count rate or flux to demonstrate spectral variability (Markowitz 2004; Sobolewska 2009). The variation of spectral slope or hardness ratio (termed color variation in UV/optical studies) can be measured as a function of timescale (Sun 2014; Zhu 2016; Wu 2020). Meanwhile, the root mean square (rms) spectrum, which measures X-ray variability amplitude as a function of energy (Vaughan 2003; Sesar 2007; Zuo 2012), is also widely adopted. The rms spectrum can be obtained for different frequency/timescale ranges (Middleton 2009; Uttley 2014; Hu 2022). Assuming variability at different X-ray energies is perfectly correlated, higher variability amplitude at lower energy is equivalent to “softer-when-brighter” and vice versa. Consequently, the correlation between variability at various energies (McHardy 2004; Epitropakis 2017) should also be examined, such as with the cross-correlation function (CCF).

Although X-ray spectral variability in AGNs has been widely studied, individual studies typically adopt only a single approach (or a limited few), hindering a full understanding of spectral variability behaviors. Furthermore, the timescale dependence of the “softer-when-brighter” trend has only been studied in one source (NGC 4051, Wu 2020).

Ark 120 is a Seyfert 1 galaxy at redshift 0.0323, with an estimated central SMBH mass of ~$1.5 \times 10^8\ M_\odot$ (Peterson 2004) and a low Eddington ratio of ~0.05 (Vasudevan 2007). It is considered a “bare” nucleus without detected UV/X-ray absorption (Crenshaw 2001; Vaughan 2004), making it an ideal target to probe intrinsic X-ray spectral variability. Ark 120 has been observed six times by XMM-Newton (Jansen 2001), each with duration $>$ 100 ks. These observations have been presented in numerous studies (Vaughan 2004; Matt 2014; Mallick 2017; Lobban 2018; Porquet 2018; Nandi 2021). In this work, we re-analyze these XMM-Newton exposures using all the aforementioned approaches to uncover the intriguing yet complex X-ray spectral variability behaviors in Ark 120, most of which have not been previously discovered or adequately interpreted. We further demonstrate that combining these various approaches is essential, as any single method alone would be insufficient to fully describe the complicated spectral variability we present.

This paper is organized as follows. We present the XMM-Newton data and reduction process in Section 2. In Section 3 we reveal the spectral variability using various approaches, followed by discussion in Section 4.

2. The XMM-Newton Data and Reduction

Ark 120 has been observed six times by XMM-Newton. Although these observations have been well studied in the literature (Vaughan 2004; Matt 2014; Mallick 2017; Porquet 2018; Nandi 2021), we provide a summary of the six exposures in Table 1, their corresponding spectra in Figure 1, and light curves in Figure 2 for the convenience of readers.

We focus on data obtained with the EPIC-pn detector (Struder 2001), operated in small window mode for all six observations. Except for the second exposure (Obs ID 0693781501, which used the medium filter), all other exposures were obtained with the EPIC thin filter.

We use the XMM-Newton Science Analysis System (SAS, version 20.0.0) and the Current Calibration Files (CCF 3.13) to process the raw data. Following the procedures described in Kang (2023), we filter out high background intervals and extract source spectra within a circular region of radius 60 , with background from nearby source-free regions. The pile-up effect is checked using the SAS task epatplot and is considered negligible for all exposures. The source spectra are rebinned to have a minimum of 50 counts per bin to enable χ^2 statistics.

To illustrate the soft X-ray excess clearly seen in the literature, we fit the spectra within 3–10 keV (excluding the 5–8 keV range to avoid the influence of the broad Fe Kα line) with pexrav (Magdziarz 1995) absorbed by Galactic column density $N_H = 1.4 \times 10^{21}$ cm^{-2} (Kalberla 2005). Because the reflection fraction R of pexrav cannot be well constrained from XMM-Newton spectra alone, we fix R at ~0.70 as measured through joint fitting of NuSTAR and XMM-Newton spectra after applying inter-instrument calibration correction. Extensive spectral fitting is beyond the scope of this work.

The X-ray spectra are dominated by the power-law component above 2 keV, with clear contribution from the soft X-ray excess below 2 keV. In this work, we utilize the softness ratio defined as the count rate ratio of 2.0–4.0 keV to 4.0–10.0 keV to probe the spectral variation of the power-law component. We also explore the spectral variability using the count rate ratio of 0.5–2.0 keV and 2.0–10.0 keV, which could be affected by both the power-law component and the soft X-ray excess.

We extract background-subtracted light curves for 0.5–2 keV, 2–4 keV, 4–10 keV, 0.5–10 keV, and 2–10 keV bands separately (each with a time bin of 1000 s), using the epiclccorr task and applying both relative and absolute corrections to account for various effects that affect detection efficiency and enable direct use of count rates and count rate ratios between bands for spectral variability analysis. The difference in transmission between the EPIC thin and medium filters is negligible for this work. In Figure 2 we plot the EPIC-pn light curves and softness ratios to illustrate the flux and spectral variability of Ark 120.

Significant flux variations in different bands are clearly seen in all exposures. Meanwhile, variations in spectral slope (softness ratio) are also visible in most exposures, particularly between 0.5–2.0 keV and 2.0–10.0 keV. We further examine the variations of the softness ratio in Section 3.1 and the rms spectra in Section 3.2. Additionally, we observe that the variability in various bands is generally well-correlated, with the exception of Obs ID 0721600501, where the 0.5–2.0 keV and 2.0–10.0 keV variations are anti-correlated. The correlation between different bands will be discussed in Section 3.3. Two individual exposures with exceptional spectral variability behaviors will be examined further in Section 3.4.

3.1. The "Softer-when-brighter" Trend

We first explore the "softer-when-brighter" diagram of Ark 120 by plotting two softness ratios (SR1: 2.0–4.0 keV/4.0–10.0 keV; SR2: 0.5–2.0 keV/2.0–10.0 keV) against corresponding total count rates (2.0–10.0 keV and 0.5–10.0 keV, respectively). As noted above, while SR1 is dominated by spectral variability of the power-law continuum, the soft X-ray excess may contribute significantly to SR2.

3.1.1. 2.0–4.0 keV/4.0–10.0 keV

In Figure 3 (SR1 versus 2–10 keV count rate) we see a clear "softer-when-brighter" trend when all observations are combined. The best-fit linear slope of this trend is depicted in the plot, with $\chi^2/\mathrm{dof} = 1.21$, suggesting that an empirical trend alone is insufficient to describe the spectral variability, similar to findings for NGC 4051 (Wu 2020).

Indeed, when we examine individual exposures in Figure 3, we do not find a significant "softer-when-brighter" trend in any single exposure. Particularly, the last exposure (Obs ID 0721600501) exhibits a contrary "harder-when-brighter" trend (see the best-fit regression slopes k marked in the plot). These facts demonstrate that the spectral variability within 2.0–10.0 keV in Ark 120 cannot be fully described by a single empirical "softer-when-brighter" trend, and the absence of this trend in individual exposures suggests the spectral variability is timescale-dependent, as revealed in NGC 4051 (Wu 2020).

Following Wu (2020), we further explore the timescale dependence of spectral variability by plotting the ratio of structure functions in two bands (see Figure 4). The structure functions in 2.0–4.0 keV and 4.0–10.0 keV are obtained using the equation (see also di Clemente 1996, Vanden Berk 2004, Zhu 2016):

$$\mathrm{SF}(\tau) = \frac{1}{N(\tau)} \sum_{i,j} \left[\log(CR_{i,j}) - \langle \log(CR) \rangle\right]^2 - \sigma_{i,j}^2$$

where $\log(CR_{i,j})$ represents the logarithmic count rates at two epochs i and j in the light curve, $\sigma_{i,j}$ the corresponding logarithmic statistical errors, and τ the lag between the two epochs. The uncertainties in the structure functions are obtained through bootstrapping the data points in the light curves (Peterson 2001). According to Zhu (2016), the ratio of the two structure functions can quantify the "softer-when-brighter" trend as a function of timescale.

From the lower panel of Figure 4 we clearly see a prominent "softer-when-brighter" trend (with SF ratio > 1.0) on long timescales ($> 10^7$ s), which disappears on short timescales ($< 10^5$ s). We even see a marginal "harder-when-brighter" trend (with SF ratio < 1.0) at timescales < 40 ks. Overall, the timescale dependence of X-ray spectral variability we reveal in Ark 120 is similar to that seen in NGC 4051 (Wu 2020).

3.1.2. 0.5–2.0 keV/2.0–10.0 keV

We repeat the analysis from Section 3.1.1 but now using 0.5–2.0 keV and 2.0–10.0 keV light curves. Similarly, we see a clear "softer-when-brighter" behavior ($k = 3.69 \pm 0.07$) in the long-term variation when considering all exposures together (see Figure 5, SR2 versus 0.5–10 keV count rate). We note that Lobban (2018) presented a figure quite similar to our Figure 5 (see their Figure 3), plotting the hardness ratio ($H + S/H - S$, where H refers to the 1–10 keV band count rate and S refers to the 0.3–1 keV band count rate) versus 0.3–10.0 keV count rate for the same six XMM-Newton exposures of Ark 120, but without further interpretation beyond pointing out the long-term "softer-when-brighter" behavior.

The similar long-term "softer-when-brighter" behaviors seen in Figures 3 and 5 suggest that while the hard X-ray power-law component follows a "softer-when-brighter" trend on timescales of years, the soft X-ray excess varies generally in correlation with the power-law on such long timescales. This long-term correlation can also be seen in Figure 1, where the strength of the soft excess (see the data-to-model ratio plot in the lower panel) exhibits only weak variability between observations while the total count rate varies by a factor > 2 (see Figure 5).

Partially thanks to the much higher count rate in the 0.5–2.0 keV band, we see much more complicated spectral variations when examining individual exposures. In the first exposure, we see a marginal "harder-when-brighter" behavior ($k = -2.91 \pm 1.62$), while in the second, third, and fifth exposures we see "softer-when-brighter" slopes similar to that derived from all exposures combined. However, the third exposure appears significantly softer compared with the overall trend (the dashed line in Figure 5), and the fifth exposure appears systematically harder. The χ^2/dof is 4.47 when all exposures are combined, and > 1.2 for most individual exposures. These facts indicate that a simple empirical "softer-when-brighter" trend is far from sufficient to explain the X-ray spectral variability within 0.5–10.0 keV.

More strikingly, we see a "V"-shaped variation in the fourth exposure in Figure 5. Examining the light curves in Figure 2, we find that in this exposure the softness ratio SR2 (0.5–2.0 keV/2.0–10.0 keV) switches from "harder-when-brighter" during the first 50 ks to "softer-when-brighter" after 50 ks. Additionally, a much steeper slope ($k = 21.14$) is seen for the sixth exposure. The abnormal spectral variability in these two individual exposures will be investigated further in Section 3.4.

Meanwhile, the timescale dependence of the "softer-when-brighter" behavior (revealed using 0.5–2 keV and 2–10 keV light curves) is displayed in Figure 6. The timescale dependence is similar to that depicted in Figure 4, indicating a much weaker "softer-when-brighter" behavior at shorter timescales.

3.2. The rms Spectra

We also examine rms spectra to investigate the dependence of variability amplitude on energy. An observation with a "softer-when-brighter" trend will have a soft rms spectrum (i.e., stronger variability at lower energy), and vice versa. Similar to Section 2, we extract light curves within eight energy bins between 0.5 and 10 keV. Following McHardy (2008), we calculate the frequency-resolved fractional rms and its error for each light curve based on the power spectral density (see also Vaughan 2003, Poutanen 2008, Jin 2017, Hu 2022). We compute the rms spectra in two frequency ranges (high: $> 10^{-4}$ Hz, and low: $< 10^{-4}$ Hz) for all six observations, as shown in Figure 7.

When focusing on the spectral range above 2 keV, we do not find clear energy dependence in the rms spectra due to limited photon counts, except for the sixth exposure where the low-frequency rms spectra increase with energy at > 2 keV. This is consistent with the patterns shown in Figure 3, where we do not see a "softer-when-brighter" trend in any exposure at > 2 keV, but do see a "harder-when-brighter" trend in the sixth exposure. We also find that at > 2 keV, the high-frequency rms spectra are marginally harder than the low-frequency ones in the second, third, and fifth exposures, supporting the timescale dependence of the "softer-when-brighter" trend above 2 keV shown in Figure 4.

When the spectral range below 2 keV is included, we clearly see soft low-frequency rms spectra in the second, third, and fifth exposures, consistent with the "softer-when-brighter" trend demonstrated in Figure 5. Again, the high-frequency rms spectra appear harder than the low-frequency ones in all but the sixth exposure, supporting the timescale dependency shown in Figure 6.

The low-frequency rms spectrum of the sixth exposure is exceptional, exhibiting a "V" shape with minimum variability around 2.0 keV. Such an abnormal rms spectrum was also noted by Mallick (2017), who presented rms spectra (8–500 $\times 10^{-6}$ Hz) for the four XMM-Newton exposures obtained in 2014 (the third through sixth exposures in this work). Mallick (2017) modeled the rms spectra assuming the primary continuum (NTHCOMP) varies in photon index Γ and normalization, and the soft excess varies in luminosity. However, they did not address why the sixth exposure is exceptional in showing a "V"-shaped rms spectrum. Moreover, the sixth exposure also exhibits an abnormally steep "softer-when-brighter" slope in Figure 5, for which we do not yet have an interpretation based on its rms spectrum.

Furthermore, during the fourth exposure we observed a transition from "harder-when-brighter" to "softer-when-brighter" (Figure 5). No clue about this transition can be extracted from the rms spectrum for the whole exposure. The two exposures (the fourth and sixth) with abnormal spectral variability will be discussed further in Section 3.4.

3.3. The Cross-Correlation Function

In attempting to understand the anomalous spectral variability of the sixth exposure (i.e., “harder-when-brighter” in Figure 3 but exceptionally steep “softer-when-brighter” slope in Figure 5, and the abnormal “V”-shaped rms spectrum in Figure 7), we noticed that its 0.5–2.0 keV and 2.0–10.0 keV light curves exhibit opposite variation trends. In other words, the variability in 0.5–2.0 keV is inversely correlated with that in 2.0–10.0 keV. We calculate the CCF to assess the correlation between variability in different bands.

Using 1 ks binned light curves, we calculate the CCF between variability in different bands. Since no clear lag is detected, we simply derive the CCF values at zero lag and plot them for all six XMM-Newton exposures in Figure 8. The CCF values at zero lag are also obtained for two frequency ranges (high: $> 10^{-4}$ Hz and low: $< 10^{-4}$ Hz).

We find that low-frequency variations are well correlated (with CCF values close to 1.0) between 2–4 keV and 4–10 keV in all six exposures, and between 0.5–2 keV and 2–10 keV in all but the sixth exposure. The correlation between high-frequency variations is generally weaker, likely due to Poisson noise. The sixth exposure appears exceptional in the CCF analysis, showing strong correlation between variations in 2–4 keV and 4–10 keV, but strong negative correlation between variations in 0.5–2 keV and 2–10 keV. The nature of this exceptional variation is explored further below.

3.4. The Abnormal Spectral Variability in the 4th and 6th Exposures

We have previously demonstrated that the 0.5–10 keV spectral variability of Ark 120 transitioned from “harder-when-brighter” to “softer-when-brighter” during the fourth exposure (Figure 5). This transition is absent in the 2–10 keV band spectral variability (Figure 3), indicating that the abnormal spectral variability could be attributed to the soft X-ray excess component below 2 keV. In Figure 3 we see that during the fourth exposure, Ark 120 exhibited no significant spectral variability within 2–10 keV (i.e., with k statistically consistent with zero and $\chi^2/\mathrm{dof} \sim 1.0$, as labeled in Figure 3).

Assuming no spectral variability of the power-law component, we estimate the expected contribution from the power-law component to the observed 0.5–2.0 keV light curve based on the observed 2–10 keV light curve (using the best-fit spectral model from Figure 1). We subtract the power-law contribution and obtain the light curve for the pure soft excess component (Figure 9). We can clearly see that during the first 50 ks of the fourth exposure, the variation of the soft excess component does not follow that of the power-law. Specifically, while the count rate of the power-law component increases with time, the count rate of the soft excess component remains unchanged or even slightly decreases. This could well explain the “harder-when-brighter” trend within 0.5–10 keV seen during the first 50 ks of the exposure. After 50 ks, the variation of the soft excess began to follow that of the power-law but with larger amplitude, and the spectral variability thus switched to “softer-when-brighter.” This transition can also be clearly seen in the different rms spectra between 0–50 ks and after 50 ks (Figure 10). Therefore, we conclude that the abnormal X-ray spectral variability during the fourth exposure is due to variation of the soft excess that can be independent of the power-law variation. The light curve of the pure soft excess component (green) in Figure 9 appears to lag behind the power-law component (yellow), with our CCF analysis yielding a lag of $25.5^{+3.5}_{-3.5}$ ks. However, this lag is likely unreliable due to the limited duration of the light curves, which spans only about four times the lag. Notably, if we exclude the first 50 ks, the lag disappears entirely. Additionally, this observed lag is much larger than the 900 s soft X-ray lag previously detected in this source (Lobban 2018), further suggesting it may be spurious.

We then examine the abnormal spectral variability in the sixth exposure, which is exceptional in three aspects: (1) it shows a “harder-when-brighter” pattern within the 2–10 keV range (Figure 3) but exhibits a very steep “softer-when-brighter” trend within the 0.5–10 keV range (Figure 5); (2) it features a “V”-shaped rms spectrum with minimum variability around 2 keV (Figure 7); and (3) there is strong correlation between variations in the 2–4 keV and 4–10 keV ranges, but negative correlation between the 0.5–2 keV and 2–10 keV ranges (Figure 8).

We divide the exposure into six intervals (see Figure 11) and extract their spectra separately. To visualize variations between spectra from different intervals, we adopt the spectral ratio method of Zhang (2018), plotting the ratio of the spectrum from each interval to that of the third interval. In the spectral ratio plot we see power-law-like ratio spectra pivoting at around 2 keV. The slopes of the ratio spectra below 2 keV appear consistent with those above 2 keV, indicating that the variations of the soft excess follow those of the power-law component well.

The exceptional X-ray spectral variation in this exposure can thus be attributed to the power-law spectrum pivoting at around 2 keV, which could easily explain all the aforementioned abnormal spectral variability: (1) “harder-when-brighter” within 2–10 keV, but “softer-when-brighter” within 0.5–10 keV; (2) “V”-shaped rms spectrum; and (3) positive correlation between variations in 2–4 keV and 4–10 keV, but negative correlation between 0.5–2 keV and 2–10 keV.

We note that a pivoting power-law has been adopted to describe the spectral variability of AGNs and X-ray binaries (Zdziarski 2003). However, pivoting at low energy, such as at 2 keV as discovered here, is rare, as Seyfert galaxies generally have pivot energies $\gtrsim 10$ keV (Zdziarski 2003). Indeed, “softer-when-brighter” is naturally expected for a much higher pivot energy. Conversely, for a much lower pivot energy, we would expect “harder-when-brighter” within the energy range above the pivot energy, and “softer-when-brighter” below it. For an energy range covering the pivot energy (such as 0.5–10 keV here), the term “brighter” becomes misleading because while the flux above the pivot energy increases, the flux below it decreases, thus the spectral variability cannot be simply described as “softer-when-brighter” or “harder-when-brighter.”

The sixth exposure does not have distinct X-ray flux or power-law spectral slope compared with other exposures (Figure 1), so it is not clear what drives such abnormality. Within the framework of thermal Comptonization, the output X-ray spectrum is determined by many factors, including the energy and number of seed photons that are up-scattered, and the geometry, opacity, and temperature of the corona. A pivoting power-law implies a finely tuned situation where when more seed photons are up-scattered to energies above the pivot energy, fewer are up-scattered to energies below it. For instance, a pivoting power-law could be reproduced if the total number of X-ray photons stays constant but the opacity of the corona changes (e.g., see Figure 3 of Titarchuk 1994), where higher opacity yields a flatter spectrum. Similarly, if the total number of X-ray photons stays constant, changes in coronal temperature could also produce a pivoting power-law, as a hotter corona produces a harder spectrum.

Considering that many factors could be involved, it is hard to draw a clear physical picture. We note that the variation of XMM-OM UVW2 flux of Ark 120 seems to match well the variation of the 0.3–10 keV flux during this exposure (see Figure 1 of Lobban 2018), suggesting that variation in seed photon flux may have played a role. We also note that while two NuSTAR observations of Ark 120 have been obtained, simultaneous with the second and fifth XMM-Newton exposures, respectively, only lower limits to the high-energy cutoff could be derived for these exposures (Kang 2023), and thus we are unable to examine the variation of coronal temperature in Ark 120.

Nevertheless, the low pivot energy we discovered indicates such events should be rare, occurring when the total number of X-ray photons changes little but the spectral slope changes significantly. This rarity suggests that specific conditions must be met for this phenomenon to occur, possibly involving a delicate balance in the properties of the X-ray corona and seed photon population. Further detailed analysis and comparison with other Seyfert galaxies may help uncover the underlying mechanisms driving this unusual spectral behavior.

Within the 0.5–10 keV range, while a similar “softer-when-brighter” trend is observed in Ark 120 on long timescales and a weaker trend within individual exposures, there are significant deviations from a single empirical “softer-when-brighter” relationship. Particularly, the spectral variability switches from “harder-when-brighter” to “softer-when-brighter” during a single exposure. These observations can be attributed to the contribution of the soft excess component, whose variability sometimes follows and sometimes does not follow that of the power-law continuum. Note that Nandi (2021) reported a strong correlation between the long-term variation of the soft excess and the primary power-law continuum in Ark 120, and such a long-term correlation is also visible in Figure 1 where we find strong variations in continuum fluxes between exposures but weak variations in the relative strength of the soft excess. However, during the specific exposure exhibiting the transition from "harder-when-brighter" to "softer-when-brighter" within 0.5–10 keV, we find the correlation between the soft excess and power-law continuum vanishes in the first 50 ks and then reappears. Assuming the soft excess in Ark 120 originates from a warm corona (Matt 2014; Porquet 2018), our findings highlight the intricate and poorly understood relationship between variations of the warm corona and the hot corona. A future large-sample study of this correlation is essential to advance our understanding.

Finally, we stress that the X-ray spectral variability in Ark 120 is extremely complex and cannot be described by a single parameter. We have employed various techniques and tools, including multi-band X-ray light curves and corresponding softness ratio light curves, softness ratio versus count rate plots, structure functions in various bands and their ratios, rms spectra, CCFs, and ratios of X-ray spectra. As demonstrated, none of these techniques alone can fully capture the intricate nature of the variability. Even with all these methods, additional efforts are needed to segment a single exposure into different intervals to better understand the variability. The variability might be driven by multiple factors, including changes in the accretion rate, variations in coronal temperature or geometry, and fluctuations in the seed photon population. Such detailed analyses not only highlight the intricate nature of AGN variability but also emphasize the need for multi-faceted approaches in studying these phenomena. Future studies incorporating even more sophisticated techniques and larger data sets will be crucial for unraveling the complex mechanisms governing X-ray variability in Seyfert galaxies like Ark 120.

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