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ABSTRACT

Despite advances in our understanding of low-luminosity active galactic nuclei (LLAGNs), the fundamental details about the mechanisms of radiation and flare/outburst in hot accretion flow are still largely missing. We have systematically analysed the archival Chandra and NuSTAR X-ray data of the nearby LLAGN M81*, whose $L_{\text{bol}} \sim 10^{-3} L_{\text{Edd}}$. Through a detailed study of X-ray light curve and spectral properties, we find that the X-ray continuum emission of the power-law shape more likely originates from inverse Compton scattering within the hot accretion flow. In contrast to Sgr A*, flares are rare in M81*. Low-amplitude variation can only be observed in soft X-ray band (amplitude usually $\leq 2$). Several simple models are tested, including sinusoidal-like and quasi-periodical. Based on a comparison of the dramatic differences of flare properties among Sgr A*, M31*, and M81*, we find that, when the differences in both the accretion rate and the black hole mass are considered, the flares in LLAGNs can be understood universally in a magnetohydrodynamical model.

Key words: accretion, accretion discs – galaxies: active – galaxies: individual: M81* – galaxies: nuclei – X-rays: galaxies.

1 INTRODUCTION

Consensus has been reached that, low-luminosity active galactic nuclei (LLAGNs), whose bolometric luminosity $L_{\text{bol}} \lesssim (1–2)$% $L_{\text{Edd}}$, are distinctive to their bright/luminous cousins (e.g. Ho 2008; Heckman & Best 2014), i.e. LLAGNs lack the big blue bump in optical/UV and the relativistic Fe line in X-rays. The reflection component in X-rays is also weak. Theoretically, luminous AGNs are believed to be powered by a cold thin accretion disc (Shakura & Sunyaev 1973), while LLAGNs are powered by a hot accretion flow [e.g. advection-dominated accretion flow (ADAF); Narayan & Yi 1994, for reviews see Ho 2008; Yuan & Narayan 2014]. Typically, relativistic jets are also observed in LLAGNs. The significant change in accretion mode among LLAGNs and bright AGNs also leads to dramatic changes in AGN feedback (e.g. Fabian 2012; McNamara & Nulsen 2012; Heckman & Best 2014), where jet, wind, and radiation from LLAGNs will have significant impacts on the gas dynamics (thus star formation) of the host galaxy.

However, it remains unclear how the cold to hot (and reverse) accretion state transition actually occur (see Yuan & Narayan 2014 for a summary of various theoretical models). Accretion in some BH systems may be partly cold and partly hot. Moreover, in the theory of hot accretion flow, flares are expected to be generated by magnetic reconnection events (e.g. Yuan et al. 2009; Li et al. 2015, see Section 4.2 below). Although the flares are indeed observed in the ultra LL system Sgr A* (Galactic centre; e.g. Yusef-Zadeh et al. 2009; Neilsen et al. 2013), their existence in other more brighter LLAGNs remains unclear yet. What drives such difference has not been systematically examined yet.

These motivate us to investigate M81*, a nearby LLAGN (Peimbert & Torres-Peimbert 1981; Filippenko & Sargent 1989) located at a distance $d = 3.61^{+0.21}_{-0.19}$ Mpc (Tully, Courtois & Sorce 2016). M81* is also classified as a low-ionization nuclear emission-line region (LINER; Heckman 1980). The bolometric luminosity of M81* is $L_{\text{bol}} \approx 1.1 \times 10^{-3} L_{\text{Edd}}$ (Ho, Filippenko & Sargent 1996; Nemmen, Storchi-Bergmann & Eracleous 2014), where the BH mass is $M_{\text{BH}} = 7 \times 10^7 M_\odot$ (Devereux et al. 2003). Thanks to its proximity in distance, several multiwavelength monitoring campaigns have been carried out (e.g. Markoff et al. 2008; Miller et al. 2010). A clear stationary core and a one-sided jet structure is observed (Bietenholz, Bartel & Rupen 2000). Moreover, a broad double-peaked Hα feature is observed in optical that suggests that outside of a truncation radius $R_T \sim 300 R_\odot$ there exists a cold thin disc (Devereux & Shearer 2007, see also Quataert et al. 1999; Xu & Cao 2009). Here $R_T = 2GM_{\text{BH}}/c^2$ is the Schwarzschild radius of BH. Considering the anticorrelation between $R_T$ and $L_{\text{bol}}/L_{\text{Edd}}$ in LLAGNs and BH binaries (e.g. Yuan & Narayan 2004), detailed studies of M81* will help to further our understanding in accretion theory, e.g. the formation of a cold thin disc.

In this work, we focus on the X-ray properties of M81*. With a hydrogen column density $N_H \approx 4.3 - 6.3 \times 10^{20} \text{cm}^{-2}$ (Young...
et al. 2018), the X-ray continuum of M81* does not suffer much absorption.\footnote{Note that the Milky Way column density in the direction of M81* is $N_H(\text{MW}) = 4.2 \times 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990).} The X-ray emission below $\sim 50$–100 keV can be well described by a simple power-law $F_\gamma \propto \epsilon^{-\Gamma - 1}$, where $\epsilon = hv$ is the photon energy. The photon index is found to be $\Gamma \sim 1.7$, i.e., $\sim 1.8$ (ASCA: Ishisaki et al. 1996; BeppoSAX: Pellegrini et al. 2000, XMM-Newton: Page et al. 2004, Chandra: Young et al. 2007, NuSTAR and Suzaku: Young et al. 2018). However, the origin of this continuum power-law X-ray emission, either from the relativistic jet or from the hot accretion flow, remains inclusive (e.g. Markoff et al. 2008; Miller et al. 2010; Nemmen et al. 2014; Xie & Yuan 2017). The hard X-rays by NuSTAR also show a cut-off at the energy $E_{\text{cutoff}} \sim 250$ keV (Young et al. 2018). The X-ray emission in high spatial resolution Chandra observation is also found to have a spatially diffuse component (Swartz et al. 2003), similar to that in Sgr A*. However, the origin of these diffuse emission remains unclear.

Fe Kα, Fe XXV, and Fe XXVI emissions are also detected in X-rays. Among them a receding velocity $\sim 2000$–3000 km s$^{-1}$ is detected in Fe XXVI (Page et al. 2004; Young et al. 2007). Recently, Shi et al. (2021) argued that the Fe XXVI lines are produced by hot outflows generated from hot accretion flow, i.e. meets a long theoretical expectation (Yuan, Bu & Wu 2012; Yuan et al. 2015, and references therein). The Fe Kα line of neutral or weakly ionized iron, on the other hand, may originate from the reflection of a truncated accretion disc or a torus of cold gas that is irradiated by the central LLAGN (Young et al. 2018). Young et al. (2018) carried out simultaneous observations in both soft and hard X-rays, where the Compton reflection hump is not detected (upper limit of $R < 0.1$, and consistent with $R = 0$). This is consistent with the observation that the cold thin disc is truncated at $\sim 300R_\odot$.

In this work, we present an analysis of archival broad-band X-ray data by Chandra and NuSTAR. The main motivation of this work is to investigate the accretion physics (i.e. origin of the X-ray emission, light curve, and possibly detected flare) in M81*, with a comparison to those in a similar but much fainter system Sgr A* ($L_{\text{bol}} \sim 1$–2 $\times 10^{37}$L$_{\odot}$, e.g Baganoff et al. 2003; Ma et al. 2019; Xie, Narayan & Yuan 2023). This work is organized as follows: Section 2 illustrates the whole data set and data reduction procedures. In Section 3, we provide the detailed analysis of the data, including light curve, broad-band spectrum, index–luminosity relationship, and flares in X-rays. Then in Section 4 we discuss the implications of our results, where a possible explanation of flare differences among different LLAGNs is provided. A brief summary is devoted to the last section.

### 2 X-RAY OBSERVATIONS

Chandra provides high spatial and spectral resolution in soft X-ray band, that are necessary to diagnose the hot plasma around SMBH, and NuSTAR supplements crucial information in the hard X-ray band, which helps to investigate the innermost region of the supermassive black hole (SMBH) in this LLAGN. Therefore we collected all the public archived Chandra and NuSTAR observations, of which M81* is in the field of view, at the time of writing this paper. No convincing short-term X-ray flare is detected during these observations, consistent with previous works (Iyomoto & Makishima 2001; La Parola et al. 2004).

21 Chandra

M81* has been monitored regularly by Chandra. Among all the 47 observations publicly available, 16 times are observed with the High Energy Transmission Grating (HETG) Spectrometer (Table 1) and the rest 31 times without it (Table 2). The absorbed soft X-ray flux of M81* is above $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ over time, this will cause, in the Advanced CCD Imaging Spectrometer array (ACIS) of Chandra, a significant pileup effect (Davis 2001). Pileup occurs when two or more photons land on the same or adjacent detector pixel within the same detector readout frame, and subsequently are either read as a single event with the summed energy or are discarded as a non-X-ray event.

During the observations with HETG Spectrometer, due to dispersing spectra of gratings, the pileup effect is negligible. Thus, we only consider $\pm 1$st-order spectra of the medium-energy gratings and the high-energy gratings for M81*. The total exposure time of filtered data is 0.44 Ms. Although the nucleus region of zeroth-order spectra suffers pileup effect, we took advantage of the high spatial resolution of Chandra on-axis imaging to analyse the iron lines in surrounding diffuse emission.

On the other hand, for the observations without grating, on-axis ones are also used for analysing the diffuse iron lines in virtue of the larger effective area. There are some observations that M81* is not the main target thus has a large off-axis location. We found that due to the broadness of point spread function (PSF) and the vignetting, pileup effect is much suppressed in this case. Although the nearby point sources are blended into the PSF of M81*, their impact is found to be small. We added up the luminosity of these nearby sources (Swartz et al. 2003; Sell et al. 2011, see fig. 1 in Young et al. 2007 for the distribution of near-nuclear point sources), which is about $5 \times 10^{38}$ erg s$^{-1}$ in 0.5–8 keV. This is 50 times lower than that of M81*, thus we do not consider their contamination below.

We reprocessed all the Chandra data with CIAO v4.10–4.11 and defla$\text{r}$ routine was implemented to remove the background flare intervals. Spectroscopic analyses were performed using ISIS v1.62. We accessed the pileup fractions of large off-axis angle observations by p$\text{ileup}$ maps tool in CIAO. Although most of them show a fraction 7–18 per cent, we argue that this tool is the indicator for on-axis sources, this fraction should be less for large off-axis sources. More sophisticated simulations with s$\text{aotr}$ace and $\text{marx}$ can help to refine it, but it’s beyond the scope of this work. Thus, we use symbol M in Table 2 to represent the moderate piled up. The unpiled up observations are estimated to be less than 5 per cent fraction.

For HETG data, X-ray flux and photon index are estimated from $\pm 1$st-order spectra. For the imaging data, although high piled-up spectra of on-axis observations can be analysed under the pileup model (Davis 2001), the model parameters can not be constrained well for individual observations due to low signal-to-noise (S/N) ratio. Thus we do not list their parameters in Table 2. Instead, for on-axis observations with long exposure, spectra from the ACIS readout streak are analysed instead. Because the exposure time of the available readout streak is about 100 times shorter than the on-axis spectrum, the S/N ratio is low in 15 observations (OBSID 5935–5949, individually). Thus we combined every 5 streak spectra together according to these intermittent observations which were proceeded in six weeks. Furthermore, pileup model also was not implemented for off-axis observations due to inaccuracy in this mode\footnote{The Chandra ABC Guide to Pileup, http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf}. And they
are estimated by extracting from an adequate region to enclose the whole PSF for large off-axis observations. For imaging observations, backgrounds are extracted from nearby source-free regions.

In ISIS, we combined ±1st-order spectra and restricted wavelength range to 1.7–28 Å for HETG data. For imaging observations, energy range 0.5–8.0 keV is noticed analogously. A minimum S/N ratio 5 or 3 in each spectra bin was adopted.

A simple model, **TBabs × powerlaw**, is applied separately to each observation, and cflux is used to get the desired flux. If residuals are significant in Fe emission region (6–7 keV), a gaussian model will be added. Actually, the emission lines are fairly weak compared to the continuum, the most significant lines are Fe Kα, Fe XXV, and Fe XXVI, whose total flux is about 1 per cent of the 2–10 keV continuum (Page et al. 2004; Young et al. 2007, 2018). The absorption model **TBabs** (Wilms, Allen & McCray 2000) with the cross sections of Werner et al. (1996). For absorbed powerlaw model, there exists a weak anticorrelation between the column density and the photon index. Thus in order to avoid this anticorrelation and compare with the results from other missions, the line of sight column density N_H was fixed to that of Milky Way, i.e. N_H = 4.2 × 10^{20} cm^{-2} (Dickey & Lockman 1990). Note that the low variation of N_H in M81* (see Section 1) leads to insignificant impact on the flux above 2 keV. The unabsorbed 2–10 keV flux of M81* is measured with convolution model cflux.

### 2.2 NuSTAR

M81* has been observed three times by **NuSTAR** using the Focal Plane Modules (FPMA and FPMB; Table 3). **NuSTAR** has a sufficient high temporal resolution, thus does not suffer pileup effect. We follow standard pipelines, nupipeline and nuproducts in HEASOFT v6.27–6.28, to extract products. Besides removing the South Atlantic Anomaly intervals from exposure time, we additionally take filtering for the ‘tentacle’ region. Without this filtering, there exist two ~1 h flare features in hard X-ray band during OBSID 60101049002 (hereafter Nu15). The data of OBSID 50401006001 is excluded from our analysis due to short exposure. During OBSID 50401006002 (hereafter Nu18), M81* was off-axis and had a distorted PSF shape. However, in hard X-rays there are no other detectable sources within 3 arcmin circular region around the nucleus, so we use an adequate size of region files to enclose the whole PSF of M81* to extract the spectra. Although we cannot exclude possible contribution from the stellar bulge, the X-ray emission is dominated by nucleus of M81* and portion increases with increasing photon energy (Swartz et al. 2003). Background counts are taken from source-free circular regions in the field of view.

The spectra of FPMA and FPMB are then combined together in ISIS. Following the methods reported in previous section, we can derive the model parameters, as reported in Table 3. All the cleaned products in this work have been extracted after the barycenter correction by each corresponding tool.

### 3 DATA ANALYSIS

#### 3.1 Light curves in X-rays

With duration of 100–200 ks (cf. Table 3), the **NuSTAR** observations provide the light curves in time-scale of ~10 h. This is shown in Fig. 1, where we consider energy bands in 3–10, 10–20, 20–40, and

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**Table 1. Observation logs of M81* with HETG by Chandra.**

<table>
<thead>
<tr>
<th>OBSID</th>
<th>Mission</th>
<th>Instrument</th>
<th>Angle$^d$ (arcmin)</th>
<th>Start date</th>
<th>Exposure$^b$ (ks)</th>
<th>$F_X^c$ (10^{-11} erg cm^{-2} s^{-1})</th>
<th>Photon index</th>
<th>Notes$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6174</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2005-02-24</td>
<td>44.61</td>
<td>$1.08^{+0.04}_{-0.03}$</td>
<td>1.80_{-0.03}</td>
<td>P</td>
</tr>
<tr>
<td>6346</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2005-07-14</td>
<td>54.48</td>
<td>$1.02^{+0.03}_{-0.03}$</td>
<td>1.88_{-0.03}</td>
<td>P</td>
</tr>
<tr>
<td>6347</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2005-07-14</td>
<td>63.87</td>
<td>$1.06^{+0.03}_{-0.03}$</td>
<td>1.87_{-0.03}</td>
<td>P</td>
</tr>
<tr>
<td>5601</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2005-07-19</td>
<td>83.07</td>
<td>$1.13^{+0.03}_{-0.03}$</td>
<td>1.85_{-0.02}</td>
<td>P</td>
</tr>
<tr>
<td>5600</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2005-08-14</td>
<td>35.96</td>
<td>$0.90^{+0.03}_{-0.03}$</td>
<td>1.88_{-0.03}</td>
<td>P</td>
</tr>
<tr>
<td>6892</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-02-08</td>
<td>14.76</td>
<td>$0.97^{+0.05}_{-0.05}$</td>
<td>1.80_{-0.04}</td>
<td>P</td>
</tr>
<tr>
<td>6893</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-03-05</td>
<td>14.76</td>
<td>$0.96^{+0.06}_{-0.06}$</td>
<td>1.85_{-0.05}</td>
<td>P</td>
</tr>
<tr>
<td>6894</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
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<td>2006-04-01</td>
<td>14.76</td>
<td>$0.96^{+0.06}_{-0.06}$</td>
<td>1.86_{-0.07}</td>
<td>P</td>
</tr>
<tr>
<td>6895</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-04-24</td>
<td>14.56</td>
<td>$0.94^{+0.06}_{-0.05}$</td>
<td>1.90_{-0.08}</td>
<td>P</td>
</tr>
<tr>
<td>6896</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-05-14</td>
<td>14.76</td>
<td>$0.95^{+0.06}_{-0.06}$</td>
<td>1.85_{-0.07}</td>
<td>P</td>
</tr>
<tr>
<td>6897</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-06-09</td>
<td>14.76</td>
<td>$0.90^{+0.06}_{-0.05}$</td>
<td>1.87_{-0.06}</td>
<td>P</td>
</tr>
<tr>
<td>6898</td>
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<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-06-28</td>
<td>14.75</td>
<td>$0.94^{+0.06}_{-0.06}$</td>
<td>1.88_{-0.05}</td>
<td>P</td>
</tr>
<tr>
<td>6899</td>
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<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-07-13</td>
<td>14.94</td>
<td>$1.04^{+0.06}_{-0.06}$</td>
<td>1.82_{-0.07}</td>
<td>P</td>
</tr>
<tr>
<td>6900</td>
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<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-07-28</td>
<td>14.41</td>
<td>$1.87^{+0.07}_{-0.08}$</td>
<td>1.77_{-0.05}</td>
<td>P</td>
</tr>
<tr>
<td>6901</td>
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<td>ACIS-S/HETG</td>
<td>–</td>
<td>2006-08-12</td>
<td>14.76</td>
<td>$1.96^{+0.08}_{-0.08}$</td>
<td>1.79_{-0.03}</td>
<td>P</td>
</tr>
<tr>
<td>20624</td>
<td>Chandra</td>
<td>ACIS-S/HETG</td>
<td>–</td>
<td>2017-12-21</td>
<td>14.76</td>
<td>$1.77^{+0.08}_{-0.08}$</td>
<td>1.81_{-0.06}</td>
<td>P</td>
</tr>
</tbody>
</table>

Notes: The data are sorted by the start time of each observation. Errors are 90 per cent confidence level for one interesting parameter.

$^a$Nominal off-axis angle of the optical centre of M81* on the detector. Blocks with no data mean on-axis (< 1 arcmin). The distortion and broadness of PSF within this separation are negligible.

$^b$Screened exposure time.

$^c$Unabsorbed flux in 2–10 keV.

$^d$Notes on zeroth-order spectra. P means piled up, N means unpiiled up, D means data are used for diffuse image. In this work, we focus on the dispersed grating spectra, they do not suffer pileup effects.
40–78 keV, respectively, for panels from top to bottom. The data are binned to 3000s.

Several results can be derived immediately from Fig. 1. First, as illustrated by the upper two panels, emission below 20 keV in M81* shows significant, \( \sim 20–30 \) per cent, variations on \( \sim 40 \) ks time-scales (see also Young et al. 2018). Considering the light crossing time-scale around a \( M_{\text{BH}} = 7 \times 10^{7} \, M_{\odot} \) BH, this implies that the variation should come from a compact \( \lesssim 110 \, R_{\odot} \) region.\(^5\)

\(^{5}\)We emphasize that, contribution from point sources in circum-nuclear region is weak compared to M81*, and no bright transients have been reported (Sell et al. 2011). Besides, although the PSFs of NuSTAR and Chandra (in off-axis mode) are large, the spatial distribution shape coincides with a central point
The light curves of M81\(\ast\) in bins of 3000 s with NuSTAR. The count rates are the mean values between the FPMA and FPMB modules, corrected for live time, PSF losses and vignetting. The background is also subtracted. Black and blue lines refer to OBSID 60101049002 and 50401006002. Each panel shows the Spearman’s rank correlation coefficient, \(sp_r\), between the count rates of each energy range and of 10–20 keV. Note that the time separation between two observations is shortened for clarity. The fluctuations of the high energy band are likely to be due to the low count rate, moreover, these short-term intervals are less than the light crossing time for the M81\(\ast\) case.

On the other hand, the hard X-ray emission above 20 keV is fairly steady. On longer time-scales, a moderate variability is observed in 2–10 keV. The 2–10 keV flux of M81\(\ast\) can vary by a factor of \(\sim 3\) at different epochs spanning \(\sim 17\) yr, as shown in Table 2. However, there seems no clear global trend (e.g. decline or increase) among different epochs.

Secondly, no flares can be detected (at S/N \(> 3\)) among the two NuSTAR observations. The apparent flare features in the hard X-ray light-curves (above 20 keV), the lower two panels of Fig. 1 are likely due to fluctuations (thus unreal), since their significance is below 2\(\sigma\) detection in M81\(\ast\). The lack-of-flare property in X-rays is confirmed and further strengthened by all the 47 Chandra observations between 2000 and 2017 (Young et al. 2007; Miller et al. 2010), where the exposure time of each observation varies from \(\sim 2–100\) ks (see Tables 2 and 3).

However, we found that a few off-axis Chandra observations (e.g. OBSID 19982) have similar long-term gradual variations as shown in NuSTAR observation, its flux almost linearly decreases over 15 percent in 67 ks as shown in Fig. 2.

Thirdly, emissions below and above 20 keV seem to have weak connections. For this investigation, we cross-correlated light curves at different energy bands to that of 10–20 keV, where we take Spearman’s rank coefficient \(sp_r\) to measure the significance of their correlations. As labelled in each panel of Fig. 1, only the 3–10 keV band has a clear but weak positive correlation (\(sp_r = 0.54\)) to the 10–20 keV band; the hard X-rays above 20 keV, on the other hand, are consistent with null correlations (\(sp_r \sim 0.2\)).

### 3.2 Broad-band X-ray spectrum

We now explore the broad-band spectral properties of M81\(\ast\). For this investigation, we utilize both Chandra/HETG data and the two long-exposure NuSTAR (0.29 Ms in total) data.

Although the origin of the X-ray continuum remains inclusive (e.g., Markoff et al. 2008; Miller et al. 2010; Nemmen et al. 2014; Xie & source. This also suggest that the variation observed should come from M81\(\ast\) itself.

The light curves of M81\(\ast\) in bins of 500 s in 2–8 keV band with Chandra during OBSID 19982. The red solid line is the best linear fit to the light curve.

The light curves of M81\(\ast\) in bins of 500 s in 2–8 keV band with Chandra during OBSID 19982. The red solid line is the best linear fit to the light curve. The spectral shape of M81\(\ast\) in X-rays is somewhat easy to model. The Compton hump is found to be absent or weak, from a joint fit of the Suzaku and NuSTAR observations of M81\(\ast\) (Page et al. 2003; Young et al. 2018). In this spirit, we joint fit the broad-band X-ray emission of Chandra and NuSTAR under a simple phenomenological TBabs \(\times\) cutoffpl model, where a free cross-normalization constant of NuSTAR spectra relative to Chandra/HETG is included. Here the spectrum of cutoffpl takes the form \(F_\nu \propto \epsilon^{-\Gamma} \exp(-\epsilon/E_c)\). Modelling based on alternative models can be found in Young et al. (2018). Again, in our work the absorption is fixed to \(N_H = 4.2 \times 10^{22}\) cm\(^{-2}\). The results are shown in Fig. 3. We find that \(\Gamma = 1.85 \pm 0.01\) and \(E_c = 192.82^{+0.39}_{-0.24}\) keV. We note that our value of \(E_c\) is lower than that (\(E_c \sim 250\) keV) reported in Young et al. (2018), due to differences in model setup.

### 3.3 The index–luminosity relation in X-rays

We now explore the correlation between the X-ray power-law photon index and the X-ray luminosity. Here we take the 2–10 keV X-ray luminosity as representative. The index–luminosity correlation can be used to probe the accretion physics, where a ‘V’ shaped relationship is observed (Yang et al. 2015, and references therein) i.e. a negative (also called as ‘harder when brighter’) relation for
Figure 4. Relationships between the photon index and X-ray flux in 2–10 keV. The abscissa is the logarithm of the X-ray Eddington ratio. The green dashed line represents the best fitting linear anticorrelation from Swift observations. The blue triangle for XMM–Newton is derived from the literature (Page et al. 2004). The data points from off-axis spectra and readout streak spectra with Chandra imaging observations (see Section 2.1) are marked both as circles. Among them, five grey data points with arrows suggest the possible intrinsic data of the moderate pileup observations (see Section 3.3).

LLAGNs (e.g. Connolly et al. 2016 for individual sources), and a positive (‘softer when brighter’) relation for bright AGNs. The index–luminosity relationship in M81+ is explored in literature, based on data of various X-ray missions (Ishisaki et al. 1996; La Parola et al. 2004; Miller et al. 2010; Connolly et al. 2016).

Fig. 4 shows a plot of photon index against the X-ray luminosity (and the Eddington ratio, defined as $L_x/(2 \times 10^{31} \text{erg \ cm}^{-2} \text{\ s}^{-1})$. The red circles and black crosses show, respectively, data from Chandra/ACIS and Chandra/HETG. We caution that, the five data points from Chandra off-axis observations (OBSID 8014, 18048, 19981, 19982, and 18053, shown by grey circles), with flux $1.1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $\Gamma \approx 1.7$, have highest pileup fraction in our data set. The pileup effect will trigger more signals of hard photon, so the intrinsic photon index should be softer than that measured. Since it is difficult to quantify this effect, we do not include these data for further analysis. The orange squares are data from NuSTAR and the blue triangle is from XMM–Newton (Page et al. 2004).

From this plot, at given luminosity, we observe a scatter of $\Delta \Gamma \approx 0.1$–0.2 in $\Gamma$. We further observe, if the two NuSTAR data points are excluded, a negative correlation between $\Gamma$ and X-ray luminosity (and flux). The Spearman’s rank correlation coefficient is $-0.46$. Note that, as shown by a green dashed line, a similar anticorrelation is also observed in Swift observations, where a flux-binned spectral modelling is adopted (Connolly et al. 2016). Clearly, there is a systemic offset between Swift data and our data, i.e. Swift observations tend to have a larger $\Gamma$ value (equivalently, softer in X-rays) at given $L_x$. The $\Gamma$ of NuSTAR also tends to be larger at given luminosity. This is probably because of contamination in soft X-rays from stellar bulge regions (Swartz et al. 2003).

Figure 5. Light curves of M81 in bins of 500 s. The black points represent combined data from Chandra HETG $\pm 1$st, $\pm 2$nd, and $\pm 3$rd orders in 1.7–28 A, the orange points are from NuSTAR in 3–10 keV band, and the red points are from Chandra ACIS-I in 0.5–8 keV band. The green points are scaled data from Suzaku XISs in 0.5–8 keV. The start date of each light curve is labelled in each panel. The corresponding OBSID is listed in Tables 1, 2, and 3. Note that normalization may be different between panels 3 and 4 (shown by red points), where they have different off-axis angles and suffer moderate pileup effect.

3.4 Weak and broad flares in X-rays

M81+ is observed to be fairly steady on decade-time-scales (i.e. from 2005 to 2014; Connolly et al. 2016). Meanwhile, as shown in Fig. 1, it also does not show large (>2) amplitude variations on time-scales of hours to days. Here, we test if there are any weak flares in M81+, with the motivation to compare with observations in Sgr A+ (See Section 4.2). Since the dynamical time-scale, i.e. the shortest time-scale of an accretion system, at $3R_\odot$ of M81+ is $t_{\text{dyn}} \equiv R V_c(R) \approx 5 \times 10^3 \text{s}$ (here $V_c \equiv (GM_{\odot}R)^{1/2}$ is the Keplerian velocity and $t_{\text{dyn}} \propto R^{3/2}$), we only explore variations on time-scales greater than several hours. Besides, as suggested by Fig. 1 (see Iyomoto & Makishima 2001; La Parola et al. 2004; King et al. 2016, and Section 4.2 below), we limit ourselves to X-rays at low energy bands, where we take $\leq 10$ keV.

3.4.1 Test 1: weak flares in soft X-rays

We checked the archived X-ray observations (including XMM–Newton and RXTE) in past two decades. The exposure time of most observations is short; thus it is challenging to test variability on hour–day time-scales. Here we first focus on the 2015 NuSTAR observation that has 202.8 ks exposure time (Nu15 hereafter, see Table 3). As shown in Fig. 1, there is evidence of a weak and broad flare in 3–10 keV band. To highlight the significance, we rebinned the data to 500 s, and the results are shown by orange points in the second panel (from top to bottom) of Fig. 5. We also include a simultaneous Suzaku observation (OBSID 710017010; Young et al. 2018) that precedes the NuSTAR data. The green points in the second panel shows the scaled count rate of averaged 3 XISs in 0.5–8 keV of Suzaku to that of NuSTAR with overlap time. The two light curves match each other well, and we hereafter refer this combined data as NS15.

We take a simple constant + gaussian model to fit the light curve in 3–10 keV. The gaussian component takes the form $F_{\text{peak}} \exp(-t^2/\sigma_{\text{flare}}^2)$. We find that, besides the stable $\approx$
0.577 ± 0.004 cts s⁻¹ emission in 90 per cent confidence level, there exists a flare that has a peak flux of $F_{\text{peak}} \approx 0.152 \pm 0.017$ cts s⁻¹ and time-scale of $\sigma_{\text{flare}} \approx 0.22 \pm 0.03$ d. If this flare is similar to that of King et al. (2016), the amplitude of the flare may be more significant in soft X-rays.

### 3.4.2 Test 2: quasi-period oscillation in soft X-rays

Below we consider an alternative interpretation. Considering there may be two local maxima within the ∼4 d observation of NS15, we may further aggressively interpret the soft X-rays of NS15 as a sinusoidal-like variation. Additional hints of such variation is also observed by data with shorter exposure times. For example, the XMM–Newton observation of M81* also reveals a decreasing trend in ∼1.4 d (Page et al. 2004, see also Figure 2), Fig. 5 shows all the long-duration X-ray observations. For completeness, we also include adjacent observations that have short gaps. These data are shown in the rest of the panels of Fig. 5, where the start time is labelled in each panel. Interestingly, despite large gaps between epochs, from the third panel of Figs 5 and 6, we find that the four epoch off-axis Chandra data also suggest a sinusoidal-like variation pattern in both soft and hard X-ray bands.

We explore if there exists a quasi-periodicity variation in the soft X-rays. Because of the low variation (only weak and broad flares exist), we find that $z$-transformed cross-correlation algorithm (Alexander 1997), which is an interpolation method for discrete sparse astronomical time series, is not suitable for our investigation. Generally, we cannot predict a convincing phase lag between NS15 and the Chandra data in 2017 January (see also Middleditch et al. 2006).

Instead, we adopt the minimum string-length (SL) method (Dworetsky 1983), which can establish the period from a relatively small number of randomly spaced observations over a long span of time. The period is chosen at the minimum of the SL (see Dworetsky 1983 for details), which is defined as

$$SL = \sum_{i=1}^{n} \left[ m_i - m_{i-1} \right]^2 + \left( \phi_i - \phi_{i-1} \right)^2 \right]^{1/2} \tag{1}$$

Here $m$ and $\phi$ are the normalized amplitude and phase of the X-ray emission if we assume there is a periodic variation (of assumed period $P$) in the signal. The normalization assures that, both the amplitude and the phase are rescaled as dimensionless quantities, with their values restricted to the −0.25–0.25 range (Dworetsky 1983). All the data are then folded into $n$ bins. Note that technically when 0th bin refers to the last $n$th bin. From equation (1), SL measures the sum of both amplitude and phase. When the assumed period $P$ matches the real period of the data, a minimum value of SL will then be derived. We note that, the absolute value of SL has no meaning, since it depends on the observational sampling, the number of bins $n$, and the intrinsic periodicity $P$.

In our analysis, we first consider NS15 and the first four epochs of Chandra only (i.e. the second and third panels of Fig. 5), and the SL at different trial periods is shown in the lower panel of Fig. 7. From this plot, a best-value period of $3.85^{+0.02}_{-0.02}$ d (at 90 per cent confidence level) is observed. Although another local minimum above 5 d is also presented, we consider it as a harmonic feature. Besides, due to limitations in the exposure of each observation, it is difficult to constrain such long quasi-period. Moreover, the shape near the minimum is fairly broad, suggesting that the flares are only quasi-periodic.

We then additionally include data of Nu18 and the rest three Chandra observations in 2017, and the result is shown in the upper panel of Fig. 7. The significance of the minimum SL at $\sim 3.8$ d is now much weakened.

### 4 DISCUSSIONS

We now discuss the theoretical implication of M81* observations. A comparison to properties of a much fainter system Sgr A* is also addressed.

#### 4.1 General picture of M81*

Fig. 8 shows a schematic picture of our understanding of accretion in LLAGNs (see Yuan & Narayan 2014). In this hot accretion-jet model, there exists a cold geometrically thin disc (shown as dark grey region; Shakura & Sunyaev 1973) that is truncated at $R_{\text{out}} \approx 300R_\odot$. Inside $R_{\text{in}}$ there exist a hot accretion flow (purple region; Narayan & Yi 1994), which also launches hot outflow from its surface. A relativistic jet (light pink region) perpendicular to accretion flow is launched from a region close to BH. We find that this picture
provides a comprehensive explanation of the observations of M81*, whose $L_{\text{bol}}/L_{\text{edd}} \sim 10^{-5}$.

It is known that in hot accretion flow the truncation radius $R_t$ decreases with increasing accretion rate (and bolometric luminosity; Yuan & Narayan 2004). With $L_{\text{bol}}/L_{\text{edd}} \sim 10^{-5}$, it is reasonable to have $R_t \sim 10^{-3} R_\odot$ in M81*. Indeed, M81* shows clear evidence that there exists a cold disc outside of $\sim 300 R_\odot$ (e.g. Quataert et al. 1999; Devereux & Shearer 2007; Xu & Cao 2009).

There are several consequences of this value of $R_t$. First, the large $R_t$ here indicates that, the opening solid angle of the cold disc to that of hard X-rays (generated at inner regions of hot accretion flow, i.e. $\lesssim 10-20 R_\odot$) will also be small. This agrees with the observational constraint of a non-detection of the Compton reflection hump (reflection parameter $R < 0.11$) in X-rays (Page et al. 2003; Young et al. 2018).

Secondly, because accretion gas outside of $R_t$ is in the form of a cold disc, we should not expect to have strong and spatially extended (up to $10^{-2} R_\odot$) bremsstrahlung emission in X-rays, a prominent component that is observed in two much fainter systems (Baganoff et al. 2003; Allen et al. 2006; Wang et al. 2013; Roberts et al. 2017), i.e. Sgr A* ($L_{\text{bol}}/L_{\text{edd}} \approx 1-2 \times 10^{-9}$), Baganoff et al. 2003; Bower et al. 2019; Ma et al. 2019; Xie et al. 2023) and M87 ($L_{\text{bol}}/L_{\text{edd}} \approx 1 \times 10^{-6}$; Prieto et al. 2016; EHT MWL Science Working Group et al. 2021). In these two systems, bremsstrahlung emission is produced by hot gas from a large region, from $10^{-4} R_\odot$ to a radius beyond the Bondi radius ($\sim 10^{2} R_\odot$).

Thirdly, the origin of continuum emission in X-rays. Our understanding to this is advanced thanks to NuSTAR observations. From a non-physical phenomenological fit of Suzaku and NuSTAR data under a cutoff power-law model, no apparent curvature can be observed within the NuSTAR band (Young et al. 2018). In this case, modelling the X-ray emission of M81* by the bremsstrahlung model requires the gas temperature being greater than 100 keV (modelling result not shown here). This is unphysical, since electrons at such high temperature ($kT/m_e c^2 \sim 0.2$) should produce strong radiation through inverse Compton scattering process. In the hot accretion-jet model of LLAGN, the most promising mechanism to produce X-rays inside $\leq R_t \sim 10^{-3} R_\odot$ of a $L_{\text{bol}}/L_{\text{edd}} \sim 10^{-5}$ system is a combination of inverse Compton scattering (dominant) and bremsstrahlung (secondary, and actually negligible) by hot electrons. At the accretion rate of M81*, a power-law spectrum of the Comptonization component is totally expected. This is consistent with observations (e.g. Chandra: Swartz et al. 2003; NuSTAR: Young et al. 2018).

There also exists a weak but extended X-ray emission outside of $R_t$ in M81* (Swartz et al. 2003). For this component, we note that hot accretion flow can generate strong outflow that can propagate distant away from the BH, as shown in Fig. 8. Numerical simulations of hot accretion flow suggest that these outflows are much hotter and more dilute (because of higher velocity) than gases within the hot accretion flow itself if exists (Shi et al. 2021). Consequently, bremsstrahlung from these hot but dilute outflowing gas may be responsible for the weak diffuse/extended X-ray emission observed in Chandra (Page et al. 2003). 8

Finally, the emission lines in X-rays. Weak Fe Kα, Fe XXV, and Fe XXVI emission (not absorption) lines are detected in X-rays (e.g. Page et al. 2003; Shi et al. 2021). The Fe Kα line of neutral or weakly ionized iron may originate from reflection of a truncated accretion disc (or a torus of cold gas) that are irradiated by the central LLAGN (Young et al. 2018). Indeed, if the observed Fe Kα line originates in reflection of Compton-thick material, a much higher reflection fraction, $R \sim 0.3-0.4$, should be measured based on the $\sim 40$ eV equivalent width of the Fe Kα line (e.g. George & Fabian 1991).

On the other hand, Fe XXV and Fe XXVI may originate from outflows in M81* (Shi et al. 2021), where they are collisionally ionized. The existence of outflow in LLAGN is indeed a theoretical expectation (Yuan et al. 2012; Yuan et al. 2015, and references therein). Observationally a receding velocity $\sim 2000-3000$ km s$^{-1}$ is detected clearly only in Fe XXVI (Page et al. 2004; Young et al. 2007). In the outflow-origin interpretation, assuming that M81* has a low inclination, both approaching and receding components can be observed in the X-ray spectrum (if observations have sufficient S/N), but the approaching one may be weakened due to asymmetry below and above the equatorial plane of the hot accretion flow (Shi et al. 2021).

### 4.2 Flares (or outbursts) in hot accretion flow: comparison to Sgr A* and M31*

In this section, we discuss the flares (or outbursts when the amplitude is high) in hot accretion flows. We summarize the flare properties of several LLAGNs, i.e. Sgr A*, M31*, and M81*, in Table 4. Besides the BH mass and bolometric Eddington ratio ($\lambda_{\text{edd}} = L_{\text{bol}}/L_{\text{edd}}$), we include in the table the occurrence rate, typical duration, and amplitude (w.r.t. non-flare state) of each flare, and spectral change (flare state, w.r.t. non-flare state).

#### 4.2.1 Basic properties of flares in LLAGNs

Observationally, strong flares are known to be rare in LLAGNs like M81* (e.g. Markoff et al. 2008; King et al. 2016, and Section 3.4), M31* ($L_x \approx 10^{39} L_{\text{edd}}$ with $M_{\text{BH}} \sim 10^8 M_\odot$; e.g. Garcia et al. 2010; Li et al. 2011), and M87.

We notice that, based on high-resolution radio observation King et al. (2016) detected a discrete knot/blob moving at a mildly relativistic velocity away from BH of M81*. Associated with this

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8The emissivity of bremsstrahlung, $j_b(bremss) \propto n^2 T^{-1/2}$ (Ghisellini 2013), decreases with decreasing gas density and increasing gas temperature.
knot ejection, they also find soft (<2 keV) X-rays a flare that precedes the radio flare by about 12 d. On the other hand, there is no clear variation in hard X-rays above 2 keV. Besides, King et al. (2016) also carried out systematic analysis of all the archival Swift data of M81* and found this event to be unique in 6 yr (2006–2011).

On the other hand, Sgr A*, with \( L_X \approx 10^{-11} L_{\text{edd}} \) and \( M_{\text{BH}} \approx 4 \times 10^6 M_\odot \), is unique in that, while it spends most of its time in quiescent state, it exhibits numerous flares in radio, submillimetre, infrared (IR), and X-rays (e.g. Baganoff et al. 2001; Genzel et al. 2003; Yusef-Zadeh et al. 2006, 2009; Dodds-Eden et al. 2011; Ponti et al. 2015; Witzel et al. 2018). The flare properties have been studied in detail in Sgr A*, e.g. based on simultaneous multiband monitoring Yusef-Zadeh et al. (2009) and statistical analysis (Neilsen et al. 2013; Li et al. 2015). Their occurrence rate is a couple times per day and the typical duration of each flare is about an hour (e.g. Neilsen et al. 2013; Yuan & Wang 2016; Witzel et al. 2018; Yuan et al. 2018). The flares are most evident in IR and X-rays (e.g. 2–10 keV), where the flux can increase by a factor of \( \gtrsim 10 \) within \( \sim 10 \) min (e.g. Genzel et al. 2003; Neilsen et al. 2013). Besides, the flares are observed to be linear polarized in near-IR and submm and have a distinct spectral index in both IR and X-rays (Zhang et al. 2017; Witzel et al. 2018; Haggard et al. 2019). The broad-band emission in flares is believed to be of synchrotron origin (e.g. Ponti et al. 2017; Yusef-Zadeh et al. 2017).

### 4.2.2 Model interpretation

Theoretically the flares in Sgr A* are interpreted as an abrupt energy releases of magnetic reconnection, where electrons can be accelerated to form the energy distribution as power-law, i.e. \( n(\gamma) \propto \gamma^{-p} \). Consequently, it will produce synchrotron emission from radio upto X-rays (and even \( \gamma \) rays). One promising model is the magnetohydynamic model, mimicking to the corona-mass-ejection phenomenon in Sun (CME model; see e.g. Yuan et al. 2009; Li et al. 2015; Čel梅jic et al. 2022; see also Dibi et al. 2014; Dexter et al. 2020 for alternative but similar models). In this model, magnetic reconnection occurred at the surface of the hot accretion flow results in the formation of flux ropes, which are then ejected out. Energetic electrons accelerated in the current sheet flow into the flux rope region and their synchrotron radiation is responsible for the flares observed. The ejection (outward motion) and expansion of plasma blob can also explain the time lags among light curves in different wavebands.

Below we try to apply this CME model to other LLAGN systems, with an emphasis on the difference in black hole mass and accretion rate among different systems. Because of marginal flare detections in M81*, we here limit ourselves to qualitative instead of quantitative comparisons.

First the flare duration. In Sgr A*, statistically the flare lasts 0.5–8 ks (Neilsen et al. 2013). Assuming that the duration of each flare follows a linear dependence on \( M_{\text{BH}} \) [notice that \( t_{\text{flare}} \propto M_{\text{BH}}(R/R_*)^{3/2} \), it will be \( \sim 10–160 \) ks in M81* and \( \sim 20–300 \) ks in M31*. Besides, among the 3Ms of observations of Sgr A*, only 39 X-ray flares are detected. Considering the duration of each flares, we may estimate an occupation fraction in time to be \( \sim 1 \) per cent. If we assume such time-occupation rate also applies to M81* and M31*, then detecting such long (hours to days) flare but with low time-occupation fraction requires high cadence monitoring, thus is admittedly challenging.

Secondly the flare amplitude. For each flare, the total magnetic power \( (E_p) \) restored before the eruption can be crudely estimated to be proportional to accretion rate \( M \) and \( M \propto m M_{\text{BH}} \). Here \( m \) defines the accretion rate in Eddington unit \( M_{\text{edd}} \). Then, the luminosity of the flare \( L_{\text{flare}} \), crudely estimated as \( \propto E_p/t_{\text{flare}} \), will be at least sensitive to BH mass, i.e. \( L_{\text{flare}} \propto M_{\text{BH}} \). Consequently, we should observe a decrease in \( L_{\text{flare}}/L_{\text{non-flare}} \) with increasing BH mass, which is consistent with the comparison between Sgr A* and M81*.

Indeed, bright flares \((\gtrsim 10 \times \text{the quiescent flux})\) are never observed in M81*, and the only clearly detected flare as reported in King et al. (2016) has \( L_{\text{flare}}/L_{\text{non-flare}} \lesssim 2 \) in soft X-rays, while it can reach \( L_{\text{flare}}/L_{\text{non-flare}} \sim 100–400 \) in Sgr A* (Neilsen et al. 2013; Zhang et al. 2017).

Thirdly, the spectral property during flare state. For simplicity, we assume the power-law distribution of electrons accelerated by magnetic reconnection, \( p \), is the same among different systems. Because the synchrotron cooling time-scale of electrons with energy \( \gamma m_e c^2 \) is \( t_{\text{cool}}(\gamma) \propto \gamma^{-1}B^{-1} \) and the magnetic field strength scales as \( B \propto M^{1/2} \propto M_{\text{BH}}^{1/2} \), we expect to have, in systems with high \( m \) and \( M_{\text{BH}} \), much shorter cooling time-scale, thus the fraction of energetic (i.e. large-\( \gamma \)) electrons will be significantly reduced. In this case, the model predicts that the flare remains invisible/undetectable in systems with high \( m \) and \( M_{\text{BH}} \). This agrees with observations that, in Sgr A* the flares can be clearly detected in both soft and hard X-rays, while in M81* they can only be observed in soft X-rays (King et al. 2016).

Finally, we note that, the CME model can also produce a QPO light curve, where the QPO period relates to the (rotational) orbital period of the moving blob (Lin, Li & Yuan 2023).

### 5 SUMMARY

In this work, we have systematically analysed the archived Chandra and NuSTAR X-ray data of M81*. We provided a detailed study of...
the light curves and statistics of spectral parameters. Our main results can be summarized as follows:

(i) The light curves of NuSTAR observations show variation in 2–5 keV X-ray band, but are quite stable in >10 keV band. No correlation can be found among different X-ray bands.

(ii) The 2–10 keV X-ray flux and photon index show a similar anticorrelation trend as observed with Swift, which is typically observed in LLAGNs and is characteristic in hot accretion flows like ADAF.

(iii) The X-ray continuum of M81* can be interpreted as dominated by inverse Compton scattering in hot accretion flow.

(iv) A variation on ∼2–5 d time-scales in soft X-ray band is detected. Several simple models are tested, i.e. isolate flares, and sinuousoidal-like ones (also supported by available long-exposure observations). Besides, due to limited exposure time, current data cannot confirm the quasi-periodicity in soft X-rays of M81*.

(v) A possible explanation of this variation is a magnetohydrodynamic model of ‘coronal-mass-ejection’ phenomenon from the hot accretion flow in M81*. When differences in both the accretion rate and BH mass are considered, the flares in other LLAGNs, including Sgr A* and M31*, can also be understood naturally.

DATA AVAILABILITY
The correlated Chandra and NuSTAR raw data used in this paper are available at CXC and HEASARC website. The reduced data underlying this paper will be shared on reasonable request to the corresponding author.

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