Evidence for A Hot Wind from High-resolution X-Ray Spectroscopic Observation of the Low-luminosity Active Galactic Nucleus in NGC 7213

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Abstract

Supermassive black holes (SMBHs) spend most of their lifetime accreting at a rate well below the Eddington limit, manifesting themselves as low-luminosity active galactic nuclei (LLAGNs). The prevalence of a hot wind from LLAGNs is a generic prediction by theories and numerical simulations of black hole accretion and has recently become a crucial ingredient of AGN kinetic feedback in cosmological simulations of galaxy evolution. However, direct observational evidence for this hot wind is still scarce. In this work, we identify significant Fe XXVI Lyα and Fe XXV Kα emission lines from high-resolution Chandra grating spectra of the LLAGN in NGC 7213, a nearby Sa galaxy hosting a ∼10^7 M_☉ SMBH, confirming previous work. We find that these lines exhibit a blueshifted line-of-sight velocity of ∼1100 km s^-1 and a high XXVI Lyα to XXV Kα flux ratio, implying for a ∼16 keV hot plasma. By confronting these spectral features with synthetic X-ray spectra based on our custom magnetohydrodynamical simulations, we find that the high-velocity, hot plasma can be naturally explained by the putative hot wind driven by the hot accretion flow powering this LLAGN. Alternative plausible origins of this hot plasma, including stellar activities, AGN photoionization, and the hot accretion flow itself, are quantitatively disfavored. The inferred kinetic energy and momentum carried by the wind can serve as strong feedback to the environment. We compare NGC 7213 to M81^*, in which strong evidence for a hot wind was recently presented, and discuss implications on the universality and detectability of hot winds from LLAGNs.

1. Introduction

Supermassive black holes (SMBHs) coevolve with their host galaxies. This is evidenced by the strong correlations between the black hole mass and global properties (bulge mass, velocity dispersion, and luminosity) of the host galaxy ( Gültekin et al. 2009; Sani et al. 2011; Kormendy & Ho 2013). Radiation, jets, and outflows from an active galactic nucleus (AGN) can impose an enormous amount of energy into the environment of the SMBH on various physical scales, suppressing cooling flows and quenching star formation. Both theoretical and observational studies have suggested that AGN feedback is the primary driver for the coevolution between SMBHs and their host galaxies (see reviews by Fabian 2012 and Kormendy & Ho 2013).

There exist two modes of black hole accretion, known as the cold mode and the hot mode (Yuan & Narayan 2014), which correspond to two respective modes of AGN feedback: radiative mode and kinetic mode. The radiative mode (or quasar mode) operates mainly in luminous AGNs whose accretion rates are close to the Eddington limit. Radiatively driven ultra-fast outflows have been detected in the X-ray spectrum of up to 35% of local luminous, radio-quiet AGNs, which are characterized by Fe XXV/XXVI absorption lines with blueshifted line-of-sight velocities of ∼10^5 km s^-1 (Tombesi et al. 2010). However, in the local universe, luminous AGNs are found in ∼10% of normal galaxies (Martini et al. 2013), while the majority of present-day SMBHs grow their mass at low rates (∼1% Eddington limit) via a radiatively inefficient, hot accretion flow (Yuan & Narayan 2014), manifesting themselves as low-luminosity active galactic nuclei (LLAGNs; Ho 2008). The kinetic mode (or jet mode) operates in these LLAGNs, which are typically radio-loud sources due to relativistic jets symbiotic with the hot accretion flow.

Theories (Blandford & Begelman 1999) and numerical simulations (Narayan et al. 2012; Yuan et al. 2012a, 2012b, 2015; Yang et al. 2021) matured over the past two decades predict that an energetic outflow in the form of an uncollimated hot wind must also be generated from the hot accretion flow. The wind has a mass outflow rate much larger than the accretion rate at the black hole horizon, thus playing a crucial role in the accretion process. Moreover, by depositing its energy and momentum to the environment, the hot wind can provide an efficient means of AGN kinetic feedback, in addition to the conventional jet-driven feedback. In fact, numerical simulations involving both the jet and the hot wind have shown that the momentum flux of the wind is always larger than that of the jet (Yang et al. 2021). The role of the hot wind in star formation and black hole growth has been investigated in detail by Yoon et al. (2019). In the influential cosmological simulations of galaxy formation and evolution, IllustrisTNG (Weinberger et al. 2017; Pillepich et al. 2018), winds from weakly accreting SMBHs are invoked to quench star formation in intermediate- to high-mass galaxies.

However, direct observational evidence of the putative hot wind remains scarce. Using Chandra non-dispersed spectrum,
Wang et al. (2013) showed that the accretion flow onto the Galactic center SMBH, Sgr A*, is consistent with an inward decreasing accretion rate, inferring the existence of an outflow, but no direct information about the outflow was yielded. Cheung et al. (2016) inferred the existence of nuclear winds in a sample of quiescent galaxies hosting LLAGNs, based on optical spectroscopic observations that reveal kiloparsec-scale bipolar emission features co-aligned with strong velocity gradients of ionized gas. Most recently, Shi et al. (2021) reported evidence for a high-velocity (∼3000 km s⁻¹), high-temperature (∼10 keV) outflow from M81*, a nearby prototypical LLAGN, based on a pair of symmetrically blueshifted and redshifted Fe XXVI Lyα emission lines in the high-resolution Chandra grating observations of this bright X-ray source. This outflow was interpreted as the long-sought hot wind produced in the hot accretion flow onto M81*, which propagates out to ∼10⁶ times the gravitational radius of the SMBH.

The finding of Shi et al. (2021) has begun to bridge a gap between observations of LLAGNs and the successful theory of hot accretion flows, as well as modern cosmological simulations of galaxy formation that require a new kinetic feedback mode from weakly accreting SMBHs, i.e., in the form of a wind. However, M81* remains the only LLAGN in which compelling evidence of a hot wind is found. In this work, we are thus motivated to search for signatures of the putative hot wind in more LLAGNs. X-ray spectra of high spectral and angular resolutions afforded by Chandra have proved to be the key for revealing the hot wind. We have examined existing Chandra grating observations of local LLAGNs (see details in Appendix A). Only one LLAGN, which resides in NGC 7213, stands out as a promising candidate for a detailed analysis presented below.

Lying at a distance of 22.75 Mpc (z = 0.00584, from the NASA/IPAC Extragalactic Database)⁵, NGC 7213 is classified as an Sa galaxy with both Syfert and low-ionization nuclear emission line region signatures, presumably powered by a central SMBH with a mass of ∼10⁸ M☉ estimated from stellar velocity dispersion (Woo & Urry 2002). Using optical integral-field spectroscopic observations of the inner galaxy, Schnorr-Müller et al. (2014) estimated a black hole mass of 8.16 ± 10⁸ M☉ from the M* BH − σ relation of Gültekin et al. (2009). Hereafter we adopt M* BH = 10⁸ M☉ as the fiducial black hole mass. The bolometric luminosity of the LLAGN is estimated to be 9 × 10³⁵ erg s⁻¹ by Starling et al. (2005) and 1.7 × 10³⁵ erg s⁻¹ by Emmanoulopoulos et al. (2012) based on broadband spectral energy distribution fitting. These yield an average Eddington ratio of λ Edd = Lbol/L_Edd ∼ 3 × 10⁻³ (L_Edd = 1.3 × 10⁵[M* BH/M☉] erg s⁻¹ is the Eddington limit), which ensures the LLAGN classification.

The LLAGN in NGC 7213 has been extensively studied in the X-ray band. Spectra obtained by XMM-Newton and Chandra observations exhibit a number of prominent emission lines, in particular the Kα line from neutral or weakly ionized Fe and highly ionized iron lines including Fe XXV Kα and Fe XXVI Lyα between 6 and 7 keV (Bianchi et al. 2003; Starling et al. 2005; Bianchi et al. 2008; Emmanoulopoulos et al. 2013). In the Chandra high-resolution grating spectrum, the Fe XXVI Lyα and XXV Kα lines appear blueshifted at a substantial velocity of ∼900 km s⁻¹ and were suggested to originate from a collisionally ionized gas (Bianchi et al. 2008). We shall revisit these lines in detail below to provide a physical understanding of their origin. The underlying continuum shows no significant Compton reflection component (Bianchi et al. 2003; Lobban et al. 2010; Ursini et al. 2015), as constrained by BeppoSAX, Suzaku, Swift, and Nuclear Spectroscopic Telescope Array (NuSTAR) observations that cover the X-ray spectrum to above tens of kiloelectronvolts. Together with the narrow neutral Fe Kα line, this suggests that the standard optically thick accretion disk may be truncated at a radius of 10⁻³–10⁴ r_g (Lobban et al. 2010), where r_g = GM* BH/c² is the gravitational radius of the black hole. A hot accretion flow is likely responsible for the bulk of the X-ray emission from this LLAGN (Lobban et al. 2010; Xie et al. 2016), although contribution from a relativistic jet is also possible and indirectly suggested by the presence of a compact radio nuclear source (Starling et al. 2005), which exhibits weakly correlated long-term variability with the X-ray nucleus (Bell et al. 2011). The four-decade-long X-ray light curve of the nucleus has also been associated with a fast-rise-exponential-decay behavior (Yan & Xie 2018), which was argued to be due to a delayed tidal disruption event.

The remainder of this paper is organized as follows. In Section 2, we describe the relevant X-ray observations and our procedures of data reduction. Our X-ray spectral analysis, including a blind search of emission lines and characterization of the underlying thermal plasma, are presented in Section 3. In Section 4, the observed X-ray spectrum exhibiting blueshifted lines from highly ionized iron is confronted with magnetohydrodynamical simulations to test the hot wind scenario. In Section 5, we show that alternative origins of the observed Fe lines, such as stellar activity, AGN photoionization, and hot accretion flow, are quantitatively disfavored, leaving the hot wind as the most plausible scenario. We also compare the cases of NGC 7213 and M81* and address general implications for LLAGN feedback. In Section 6 we summarize our results. Quoted errors throughout this work are at the 90% confidence level, unless otherwise stated.

### 2. Observations and Data Preparation

In this work, we primarily utilized two sets of X-ray data of NGC 7213: (i) Chandra spectra obtained by the High Energy Transmission Grating (HETG) in combination with the Advanced CCD Imaging Spectrometer (ACIS), which are able to resolve emission lines expected from the hot plasma around the SMBH, at a velocity resolution of 300–2000 km s⁻¹ over an energy range of 0.5–8 keV, and (ii) NuSTAR spectra to constrain the broadband continuum over 3–79 keV.

NGC 7213 was observed by Chandra/HETG on 2007 August 6 and 9 (ObsID 7742, 8590), with exposures of 115 and 35 ks, respectively. The data was downloaded from the public archive and reprocessed following the standard procedure with Chandra Interactive Analysis of Observations (CIAO) v4.13 and calibration files CALDB v4.9.5. The ±1-order grating spectra of both the high-energy grating (HEG) and medium-energy grating (MEG) were extracted using tgrsextract, for each of the two observations. For the source spectra, we adopted the default cross-dispersion half-width of 2.4″ (corresponding to 265 pc at the assumed distance of NGC 7213), which ensures the same enclosed-energy fraction (∼97%) for different wavelengths.⁶

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⁵ http://ned.ipac.caltech.edu

⁶ https://cxc.cfa.harvard.edu/proposer/POG/
The background spectra were extracted from two adjacent regions above and below the source region each with the default full-width of 19''1. The spectral extraction regions are illustrated in Figure 1 displaying a 0.5–8 keV counts image combining the two ACIS/HETG observations. Our visual examination of this image found no significant point sources that may contaminate the source and background spectra. The source shows no significant intra-observation and inter-observation variability. Hence we co-added the ±1-order spectra from the two observations, respectively, for the HEG and MEG, which results in a total clean exposure time of 148 ks. The background spectra were also co-added, which contributes to ≤2% of the source counts. We grouped the spectra to have at least one count per bin, to preserve the maximally possible spectral resolution for the subsequent spectral analysis.

NGC 7213 was targeted by NuSTAR on 2014 October 5, for an effective exposure of 101.6 ks (ObsID 6001031002). The data was downloaded and reprocessed following the standard nuproducts in the software package NuSTARDAS v1.9.2. The spectra of NGC 7213 were extracted for both focal plane modules A and B (FPMA and FPMB) with nuproducts. The source region was a circle with a radius of 100'' centered on the galaxy, while the background spectra were extracted from a concentric annulus with an inner radius of 105'' and an outer radius of 175'' (Figure 1). The spectra were similarly grouped to have at least one count per bin. Six off-nucleus point sources are present within the NuSTAR spectral extraction region. We find that their collective 0.5–8 keV flux accounts for less than 1% of the flux of the nuclear source. Thus these off-nucleus sources should have a negligible contribution to the NuSTAR spectra. We note that the source light curve shows no significant intra-observation variability.

3. Spectral Analysis

3.1. Broadband Continuum

Spectral analysis is carried out with Xspec v.12.9.1, adopting the Cash statistics (C-stat) to determine the best-fit models. To characterize the broadband X-ray continuum, we first consider a simple absorbed power-law model $C_{abs}powerlaw$, as we find no hint of excess foreground absorption in the spectra. Hereafter the absorption column density is fixed at the Galactic foreground value, $N_H = 1.08 \times 10^{20} \text{ cm}^{-2}$. The co-added MEG spectrum over 0.5–5 keV, the co-added HEG spectrum over 1–8 keV, and the FPMA/FPMB spectra over 3–79 keV are jointly fitted, excluding energies between 6 and 7.5 keV energy to avoid influence by the known Fe lines. The photon-index $\Gamma$ is tied between HEG and MEG and between FPMA and FPMB, but allowed to be different between the Chandra and NuSTAR spectra. The normalization is allowed to vary among the four spectra, to account for possible flux variation and difference in

![Figure 1. A 0.5–8 keV ACIS/HETG image combining the two Chandra observations of NGC 7213. The roll angles of the two observations differ by 180°; hence, the HEG/MEG dispersed arms of the two observations are indistinguishable here. The blue solid rectangles mark the spectral extraction region, with the adjacent dashed rectangles defining the background. The red solid and dashed circles mark the source and background spectral extraction regions for the NuSTAR observation. The insert is a zoomed-in view of the circumnuclear region. The zeroth-order spectrum of the off-nucleus emission is extracted from the solid annulus, while the corresponding background is defined by the adjacent dashed annulus.](image-url)
Figure 2. Observed broadband X-ray spectra of NGC 7213. Blue: co-added Chandra MEG spectrum; green: co-added Chandra HEG spectrum; red: NuSTAR FPMA spectrum; and black: NuSTAR FPMB spectrum. Here the spectra are grouped to have a signal-to-noise ratio greater than 3 per bin for better visualization. Error bars are of 1σ. The spectra are fitted with an absorbed power law. The lower panel shows the residual-to-error ratio. The energy range of 6–7.5 keV, where significant Fe lines are present, is excluded from the spectral fit.

Table 1

| Data and Model | C/d.o.f. (1) | Γ (2) | N\text{pl} (3) | kT\text{h} (4) | kT\text{l} (5) | v\text{h} (6) | v\text{l} (7) | N\text{h} (8) | N\text{l} (9) | N_{\text{wind}} (10) |
|----------------|-------------|-------|----------------|----------------|--------------|-------------|-------------|--------------|------------|-------------------|
| PL HEG (1–8 keV) | 4367/ 4212 | 1.723 | 5.69±0.09 | ... | ... | ... | ... | ... | ... | ... |
| MEG (0.5–5 keV) | 3750/ 3881 | 5.96±0.06 | ... | ... | ... | ... | ... | ... | ... | ... |
| FPMA (3–79 keV) | 1665/ 1592 | 4.76±0.12 | ... | ... | ... | ... | ... | ... | ... | ... |
| FPMB (3–79 keV) | 1581/ 1570 | 4.80±0.12 | ... | ... | ... | ... | ... | ... | ... | ... |
| PL+ apec\text{h} | 354/356 | 1.723 | 4.1±0.9 | 16.6±6 | ... | −1.1±0.3 | ... | 4.4±1.8 | ... | ... |
| PL+ wind | 356/358 | 1.723 | 2.4±0.2 | ... | ... | ... | ... | ... | 0.2±0.1 | ... |
| PL+ apec\text{h}+ apec\text{l} | 4287/4206 | 1.723 | 5.1±0.2 | 13±5 | 0.8±0.2 | −1.2±0.2 | 0.04±0.12 | 1.9±0.6 | 0.05±0.03 | ... |
| MEG (0.5–5 keV) | 3740/3875 | ... | ... | ... | ... | ... | ... | ... | ... | ... |

Note. (1) The fitted data set and the adopted model; “h” and “l” denote high- and low-temperature, respectively. “PL” stands for power law and “wind” denotes a synthetic wind model; (2) Cash statistics over degree of freedom; (3) Power-law photon-index; (4) Normalization of the power law, in units of 10\text{-3} ph s\text{-1} cm\text{-2} keV\text{-1} at 1 keV; (5)–(6) Plasma temperature of high- and low-temperature apec models; (7)–(8) Line-of-sight velocity of high- and low-temperature apec model, in units of 10\text{3} km s\text{-1}; (9)–(10) Normalization of high- and low-temperature apec model, in units of 10\text{-3} cm\text{-2}; (11) Normalization of the synthetic wind model, in units of 10\text{-3} cm\text{-2}. Errors are quoted at the 90% confidence level.

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The enclosed-energy fraction. The best-fit photon-index is Γ = 1.723 ± 0.013 for HEG/MEG and Γ = 1.838 ± 0.012 for FPMA/FPMB, which are consistent with previous studies (Bianchi et al. 2008; Ursini et al. 2015). The point-spread function (PSF) corrected, unabsorbed 2–10 keV flux from the Chandra spectra is ∼40% higher than that from the NuSTAR spectra, in agreement with the flux decreasing trend found by Yan & Xie (2018). The best-fit absorbed power-law models are plotted against the observed spectra in Figure 2, and the fitted parameters are listed in Table 1.
We then try to replace the power-law model with a cutoff power law (cutoffpl in Xspec), in order to test whether there is significant spectral softening at higher energies. We fit the NuSTAR spectra alone to constrain the high-energy cutoff, which results in a 3σ lower limit, $E_{\text{cut}} > 93$ keV, beyond the NuSTAR spectral coverage. This suggests no significant spectral softening and that a single power law is sufficient to account for the broadband continuum, especially at energies below 8 keV. To further examine the possible presence of a reflection component, we employ the pexmon model in Xspec, which can self-consistently calculate the reflected continuum from neutral gas and the fluorescent lines of neutral iron. In this model, the intrinsic continuum assumes a power law with an exponential cutoff. We find a best-fit $\Gamma = 1.786^{+0.013}_{-0.005}$, $E_{\text{cut}} = 184^{+32}_{-60}$ keV, and a reflection fraction $R = \frac{1}{2} < 0.06$ (3σ). During the fit, the inclination angle has been fixed at 45° to reduce model degeneracy, and we have verified that changing this parameter has little effect on the derived reflection fraction. The lack of a reflection component, also found by Lobban et al. (2010) based on Suzaku observations, indicates a truncated accretion disk.

We conclude that the broadband X-ray spectra of the LLAGN in NGC 7213 can be well characterized by a power-law model.

### 3.2. Blind Search of Lines

Now we perform a blind search of emission/absorption lines in the co-added HEG and MEG spectra, following the method described in Tombesi et al. (2010) and Shi et al. (2021). Specifically, the putative line is modeled by a Gaussian profile, whose centroid energy $E_0$ and normalization $N$ are free to vary, and the dispersion is fixed at half of the HETG resolution (0.0056 Å for HEG and 0.0111 Å for MEG). The Gaussian is added to the baseline power-law model derived in Section 3.1 (i.e., with a fixed photon-index of 1.723), progressively increasing $E_0$ channel by channel over the energy range of interest and seeking for the best-fit $N$. The improvement of C-stat, $\Delta C$, with respect to the baseline model is evaluated at each step. For each pair of ($E_0$, $N$), the confidence level of the line can be calculated according to $\Delta C$, given the fact that C-stat is asymptotically distributed as $\chi^2$. The resultant contour plots are shown in Figure 3 for the HEG spectrum between 5 and 8 keV.

Three emission lines, all with a confidence level $>95\%$, are identified from the HEG spectrum between 5 and 8 keV. We note that these lines were also identified by Bianchi et al. (2008) based on the same data set. The centroid energies of the three lines, after correcting for the systemic redshift ($z = 0.00584$) of NGC 7213, are 6.391 keV, 6.709 keV, and 7.001 keV, respectively. We have checked the robustness of line detection by varying the photon-index of the baseline power-law model between 1.70 and 1.74. The resultant confidence levels of the three lines all remain above 95%. To refine the characterization of each line, we again apply the Gaussian model, this time setting the line width as a free parameter. The Gaussian fit results, including line centroid, line width, flux, and equivalent width, are listed in Table 2.

The 6.391 keV line can be identified as the K\(\alpha\) line of neutral or weakly ionized Fe. This line is marginally resolved, with a best-fit line width of $20^{+10}_{-8}$ eV, corresponding to a velocity dispersion of $1.0^{+0.4}_{-0.3} \times 10^3$ km s$^{-1}$. The relatively low velocity dispersion and lack of significant Doppler shift suggest that this line arises from a truncated accretion disk or remote cold gas illuminated by the central LLAGN. A similar conclusion was drawn by Lobban et al. (2010). The 6.709 keV line is the weakest among the three lines and is consistent with the

![Figure 3](image-url). Significant lines between 5 and 8 keV in the co-added HEG spectrum from a blind search. The photon energy has been corrected for the systemic redshift of NGC 7213. Contours denote the improvement of C-stat ($\Delta C$) for a Gaussian line when added to the baseline continuum model. The blue, green, and red contours represent values of $\Delta C$ equivalent to confidence levels of 99%, 95%, and 68%, respectively. Three emission lines are identified at a confidence level $>95\%$. 


Fe XXV (He-like Fe) Kα triplet, which is not fully resolved by HEG. The 7.001 keV line may be a blueshifted Fe XXVI (H-like Fe) Lyα line, as previously suggested by Bianchi et al. (2008). For the rest-frame energy of Fe XXVI Lyα,7 6.966 keV, this implies a line-of-sight velocity of \(\sim 1.3 \times 10^5 \text{ km s}^{-1}\). We further consider the possibility that this line is Fe I Kβ, which has a rest-frame energy of 7.058 keV. However, this would imply a line-of-sight velocity of \(2400 \text{ km s}^{-1}\), which is inconsistent with the observed centroid of Fe I Kα. Moreover, the flux ratio between Fe I Kβ and Kα should have a canonical value of \(\sim 0.13\) (Palmeri et al. 2003), while the observed ratio between the 7.001 keV and 6.391 keV lines is substantially larger (0.4 ± 0.2). Hence we conclude that the 7.001 keV line cannot be associated with Fe I Kβ. Guided by the implied blueshift of the Fe XXVI Lyα line, we refit the blended Fe XXV Kα using a double Gaussian profile (Figure 4(a)), obtaining line centroids at 6.660\(^{+0.015}_{-0.015}\) keV and 6.722\(^{+0.017}_{-0.017}\) keV. If the two Gaussians could be, respectively, associated with the forbidden transition (rest-frame energy at 6.637 keV) and resonant transition (rest-frame energy at 6.700 keV), they would both be blueshifted with a line-of-sight velocity of \(\sim 1.0 \times 10^5 \text{ km s}^{-1}\), nicely compatible with the putative blueshifted Fe XXVI Lyα. This lends further support to the identification of the latter.

Our blind search also finds several significant emission lines between 1 and 4 keV in the MEG and HEG spectra (Figure 5), where the two gratings have a comparable line sensitivity. For these lines to be considered real, we have required that they are detected at a significance above 95\% in at least one of the two spectra and that their flux or 3σ upper limit be consistent between the two spectra. The basic properties of these lines are again derived from a Gaussian fit and listed in Table 3. From the line centroid, we identify Lyα lines of Mg XII and Ar XVIII. Both lines are unresolved and have a Doppler shift \(\lesssim 450 \text{ km s}^{-1}\). We also tentatively associate an unresolved 3.911 keV line with the resonant transition of Ca XIX Kα (rest-frame energy 3.902 keV), which would imply for a Doppler shift \(\lesssim 700 \text{ km s}^{-1}\). We note that no significant emission lines are found between 4 and 6 keV. Nor do we find any significant absorption line in the MEG and HEG spectra.

### 3.3. Modeling the Hot Plasma

The blueshifted Fe XXVI Lyα and Fe XXV Kα lines indicate a hot plasma with a substantial bulk motion. We use a phenomenological model to characterize such a plasma. Specifically, an optically thin plasma model, apec in Xspec, is applied to fit the 5–8 keV HEG spectrum, with the plasma temperature and redshift as free parameters and the abundance fixed at solar. The portion of the spectrum at lower energies is temporarily neglected, which may require an additional component as suggested by the emission lines of the low-Z elements and a small excess to the power-law continuum seen at energies \(\lesssim 1\) keV in the MEG spectrum (Figure 2). Foreground absorption is again fixed at the Galactic value. Two Gaussian lines are added to account for the Fe I Kβ and Kα lines, with a fixed line ratio of 0.13 between the two. The baseline power-law continuum is also included, with the photon-index fixed at 1.723. This composite model results in a reasonable fit (Figure 4(b)), with a plasma temperature \(kT = 16 \pm 6 \text{ keV}\), which is mainly driven by the flux ratio between the Fe XXVI Lyα and Fe XXV Kα lines. After correcting for the systemic redshift of NGC 7213, the fitted model requires a line-of-sight velocity of \(-1.1^{+0.3}_{-0.4} \times 10^3 \text{ km s}^{-1}\), consistent with the expectation from the line centroids (Section 3.2). The unabsorbed 2–10 keV of this 16 keV plasma is found to be \(\sim 4 \times 10^{41} \text{ erg s}^{-1}\).

While the HEG spectrum shows no sign of a redshifted counterpart to the blueshifted Fe lines, it is tempting to provide constraint on a potential redshifted component. To do so, we add to the above composite model a second apec component, requiring it to have the same temperature and a line-of-sight velocity exactly opposite to the blueshifted component. The upper limit of this redshifted apec is then determined by deviating the C-stat until the 3σ level is reached at the 2–10 keV flux ratio between the redshifted and blueshifted components is thus constrained to be <0.45.

The 16 keV plasma, however, cannot be responsible for the detected Kα and Lyα emission lines of the low-Z elements (Table 3), since at such a high temperature, these low-Z elements would be fully ionized. To account for these lines, we again add a second apec component to the above composite model, this time allowing both the plasma temperature and redshift to vary freely. It turns out that this new composite model provides a reasonable simultaneous fit to the 1–8 keV HEG spectrum and 0.5–5 keV MEG spectrum. Compared to the single power-law model, the composite model improves the C-stat by 80 for the HEG spectrum and 10 for the MEG spectrum for six fewer degree of freedom. The best-fit temperature of the second apec is \(0.8^{\pm0.2}\) keV, and the best-fit redshift is nearly zero, suggesting little bulk motion. The unabsorbed 0.5–10 keV luminosity of this component is \(8.7 \times 10^{39} \text{ erg s}^{-1}\). This signifies a low-T plasma that might be associated with a circumnuclear hot gas. It is noteworthy that with the addition of the low-T component, the best-fit temperature of the blueshifted high-T component becomes \(13^{\pm3}\) keV, still consistent with the value (16 keV) determined from fitting the 5–8 keV spectrum alone.

The spectral fit results in this section are summarized in Table 1.

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Table 2

| \(E_0\) (keV) | Significance | \(E_c\) (keV) | \(\sigma_E\) (keV) | \(F\) | \(EW\) (keV) |
|---|---|---|---|---|---|
| 6.391 | >99.9\% | 6.395 ±0.007 | 0.10 | 20\(^{+10}_{-8}\) | 3.1\(^{+0.8}_{-0.7}\) | 126\(^{+0.5}_{-0.8}\) |
| 6.709 | 96.7\% | 6.717 ±0.016 | 0.03 | <55 | 0.7\(^{+0.5}_{-0.4}\) | 26\(^{+0.2}_{-0.1}\) |
| 7.001 | >99.9\% | 6.996 ±0.012 | 0.011 | <99 | 1.4\(^{+0.7}_{-0.6}\) | 61.2\(^{+0.8}_{-0.3}\) |

Note. (1) Most probable line centroid energy, in units of kiloelectronvolts, determined by the blind search and corrected for the systemic redshift of NGC 7213; (2) Significance level of the line; (3) Line centroid in units of kiloelectronvolts, derived from the Gaussian fit; (4) Line width in units of electronvolts; (5) Line flux in units of \(10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}\); (6) Equivalent width in units of electronvolts. Error bars are given at the 90% confidence level, and upper limits of the line width are given at 3\(\sigma\).

Footnote: 7 Rest-frame line centroid energies throughout this work are taken from ATOMDB (http://www.atomdb.org).
3.4. Zeroth-order Spectrum of the Off-nucleus Region

We have also examined the X-ray spectrum of an off-nucleus region (Figure 6), which is extracted from the zeroth-order ACIS/HETG image and provides a meaningful constraint on the spatial extent of the thermal components found in the first-order dispersed spectra. The off-nucleus region is defined as an annulus with an inner-to-outer radius of 2″–5″ (275–550 pc; see the insert in Figure 1), which is immediately outside the first-order spectral extraction region and also avoids the potential effect of pileup caused by the bright nucleus. The corresponding background spectrum is extracted from a concentric annulus with an inner-to-outter radius of 5″–8″.

Spectra extracted from the two Chandra observations are co-added. We find that a power-law model subjected to the Galactic foreground absorption can well describe this spectrum. The best-fit photon-index of 1.7 ± 0.1 and an unabsorbed 0.5–10 keV luminosity of 2.5 × 10^{40} erg s^{-1} can be understood as the collective emission from unresolved X-ray binaries plus PSF-scattered photons from the bright nucleus.

While a thermal component is not formally required by the apparently featureless spectrum, we add an apec model to the...
fit, fixing the abundance at solar and the plasma temperature at 0.8 keV as found for the low-T component in the first-order spectra (Section 3.3). The maximum normalization of this apec is found such that the deviation of C-stat arrives at the 3σ level, which is indicated by the blue dotted curve in Figure 6. The corresponding unabsorbed 0.5–10 keV luminosity is $\sim 4 \times 10^{38}$ erg s$^{-1}$, which is $\sim 20$ times lower than that of the 0.8 keV component detected in the first-order spectrum. In terms of surface brightness, the 0.8 keV plasma is a factor of 70 times lower in this off-nucleus region, considering the underlying projected area of zeroth- and first-order spectra. This indicates that the 0.8 keV plasma is concentrated within the central $\sim 300$ pc and strengthens our above suggestion that it is tracing a circumnuclear hot gas.

4. A Hot Wind from the LLAGN as the Origin of the Fe Lines

The X-ray spectra presented in the previous section reveal the presence of a high-velocity, hot plasma in the LLAGN of NGC 7213. This is highly similar to the case of M81* (Shi et al. 2021), in which a high-velocity, hot plasma is traced by highly ionized Fe lines and interpreted as an energetic wind driven by the hot accretion flow onto the central SMBH. Here we consider this same scenario for NGC 7213, which is illustrated in Figure 7. In this schematic diagram of an inflow-outflow system around a weakly accreting SMBH, a cold thin disk dictates the accretion in flow at large radii, but becomes truncated at a radius $r_t \sim 10^3 r_g$. Inside $r_t$, the disk is replaced by a geometrically thick hot inflow. Close to the event horizon,
as 0.8\(v_k\), wind velocity as 0.6\(v_k\), temperature as 0.5\(kT_{\text{vis}}\), and the plasma \(\beta = \frac{p_{\text{gas}}}{p_{\text{mag}}} = 0.2\) at the inner boundary, where \(v_k = \frac{(GM_{\text{BH}}/r)^{\frac{1}{2}}}{r}\), \(kT_{\text{vis}} = \frac{GM_{\text{BH}}}{3r}\), \(p_{\text{gas}}\), and \(p_{\text{mag}}\) are the Keplerian velocity, virial temperature, gas pressure, and magnetic pressure, respectively. Only the toroidal magnetic field is taken into account, since the poloidal field is typically much smaller than the toroidal component at large radii as found in wind simulations (Yang et al. 2021). The grid of the simulation is extended from \(2 \times 10^3 r_g\) to \(10^6 r_g\) in radial direction. A radially injecting boundary condition is set for the inner boundary, while an outflow boundary condition is adopted at the outer boundary. The grid in the latitudinal direction is extended from \(\theta = 10^\circ\) to \(50^\circ\) to avoid the singularity of a spherical coordinate and to neglect the jet. The existence of a relativistic jet does not affect the dynamics of the wind, nor does it produce emission lines. A reflective boundary condition is set for the latitudinal direction, since we expect that the pressure from the truncated disk will confine the hot wind.

A direct outcome of the simulation is the two-dimensional (2D) distributions of density, temperature, and velocity, as shown in Figure 8. We note that the absolute scale of the density is determined by matching the synthetic wind spectrum to the observed spectrum (see Section 4.2). The synthetic wind spectrum is produced based on the simulated quantities. Specifically, we first expand the 2D grid into a 3D grid, given the axisymmetry about the jet axis and mirror symmetry with respect to the equatorial plane. We then calculate the density-weighted X-ray spectrum of each grid in the black hole rest frame, utilizing ATOMDB for a given metal abundance to include atomic transitions and bremsstrahlung. The synthetic spectrum is then calculated by integrating along a given viewing angle, i.e., the angle between the jet axis and line of sight. In this step we take into account the effect of gravitational lensing, which will boost the redshifted component, and the effect of relativistic Doppler shift, which will boost (reduce) the blueshifted (redshifted) component. Self-absorption in the hot wind is neglected, since the hot wind is expected to be optically thin, which we verify in Appendix B. However, we have considered potential absorption by the truncated thin disk, which could be optically thick to X-ray photons from behind the disk, for a certain light of sight (see illustration in Figure 7).

4.1. Wind Simulation and Synthetic Wind Spectrum

We perform a 2.5-dimensional MHD simulation with the ZEUS-MP/2 code version 1.5.19 (Hayes et al. 2006) in spherical coordinates. The black hole mass is set to be \(10^8 M_{\odot}\), based on observations (Woo & Urry 2002). The simulation setup is similar to that in Shi et al. (2021), which is briefly described here. The wind starts from the inner boundary, which is set at 2000 \(r_g\), i.e., the assumed disk truncated radius, appropriate for the moderate Eddington ratio of the LLAGN in NGC 7213 and also consistent with the narrowness of the Fe I K\(\alpha\) line (Section 3.2). We ignore a possible wind from the cold disk outside the truncated radius, which is expected to have too low temperatures to produce the highly ionized Fe. The rotational energy, kinetic energy, thermal energy, and magnetic energy of the wind are taken into account. Following Yuan et al. (2015) and Yang et al. (2021), we set the rotation velocity the observed Fe lines.

Figure 7. Schematic diagram of the inflow-outflow system around the central SMBH in NGC 7213 (represented by the black circle). The pair of gray triangles represents the geometrically thick hot accretion flow. The black stripes along the equatorial plane mark the truncated thin disk, while the vertical yellow stripe denotes a relativistic jet. The blue and red cones with stripes along the equatorial plane mark the truncated thin disk, while the yellow triangles represent the geometrically thick hot accretion flow-out. The black circle with a line represents a relativistic jet. The blue and red cones with stripes along the equatorial plane mark the truncated thin disk.

4.2. Comparison with the Observed HEG Spectrum

The synthetic wind spectrum is compared with the observed HEG spectrum over 5–8 keV. Added to the wind model are again the baseline power law and two Gaussian lines representing Fe I K\(\alpha\) and K\(\beta\). We emphasize that this comparison is not a formal fit to the observed spectrum. Rather, our aim is to examine whether the synthetic spectrum of the hot wind, naturally arising from the standard paradigm of hot accretion flow onto a weakly accreting SMBH, can provide a satisfactory description to the observed spectrum, in particular the blueshifted Fe emission lines.

By construction of our wind simulation and synthetic spectrum, the primary free parameter is the viewing angle. We find that a viewing angle of 80° results in a synthetic spectrum that best matches the observed spectrum (Figure 9). In this case, the bulk of the highly ionized Fe lines are produced in the radial range of \(10^3–10^5 r_g\), where the plasma
temperature ranges between $3 \times 10^7$–$3 \times 10^8$ K and the radial velocity ranges between 1500 and 8000 km s$^{-1}$ (Figure 8).

The large viewing angle has two main effects. First, the projected line-of-sight velocity of the Fe line prevalent region takes values of $\sim$1100 km s$^{-1}$, compatible with the observed Doppler shift. Second, the redshifted component, which arises from behind the equatorial plane, is largely obscured by the truncated disk. This breaks the intrinsic symmetry between the blueshifted and redshifted components as a result of the intrinsic symmetry of the bipolar wind about the equatorial plane.

Figure 8. Plasma temperature (a) and density (b) distribution of the hot wind from the MHD simulation. The radial velocity field is overlaid with arrows. The $y$-axis follows the jet axis, and the $x$-axis defines the equatorial plane of the truncated disk. Regions occupied by the jet or the disk have been excluded.

Figure 9. The synthetic wind spectrum (green dotted curve) for a viewing angle of 80° and an Fe abundance of twice solar is confronted with the observed spectrum. Other symbols are the same as in Figure 4.
plane by design, and provides a natural explanation to an unexplained redshifted counterpart to the blueshifted Fe XXVI Lyα line in the observed spectrum (Section 3.3). Quantitatively, the thin disk has a large hydrogen column density of $4.3 \times 10^{26} \left( \alpha / 0.1 \right)^{-4/5} \left( m / 0.001 \right)^{7/10} \left( r / 2000 \right)^{-3/4} \text{ cm}^{-2}$ along the direction perpendicular to the disk plane, for the black hole mass $M_{\text{BH}}$, the accretion rate normalized by the Eddington limit $\dot{m}$, and viscosity parameter $\alpha$ suitable for NGC 7213 (Kato et al. 2008). The corresponding effective optical depth of electron scattering, $\tau_{\text{e}} \sim 4.7 \times 10^{11} \left( \alpha / 0.1 \right)^{-4/5} \left( M_{\text{BH}} / 10^6 \text{ M}_\odot \right)^{1/5} \left( n / 0.001 \right)^{1/5}$, is sufficiently high to block the X-ray photons from behind the disk.

Alternatively, the weak or absent redshifted component may be due to an intrinsic asymmetry of the hot wind. As discussed in Shi et al. (2021), the gas densities of the wind above and below the equatorial plane can deviate from each other at a level of $\sim 25\%$ on the dynamical timescale ($\sim 10$ yr) of the wind, which can lead to a $\sim 50\%$ difference between the observed redshifted and blueshifted components. While such an explanation was offered for the moderate inequality between the observed redshifted and blueshifted Fe XXVI Lyα lines in M81, the substantially weaker redshifted component in the present case of NGC 7213 disfavors an intrinsic variability as the primary cause.

A second tunable parameter in the synthetic spectrum is the Fe abundance. Initially, we have assumed a solar abundance as adopted in the apec models (Section 3.3). However, the equivalent width of the Fe XXVI Lyα line derived from the synthetic spectrum is 32 eV, which is only about half of the observed value (61.2 eV). Hence we adopt a synthetic spectrum with the Fe abundance being twice solar, which leads to an equivalent width of 45 eV for Fe XXVI Lyα with the C-stat improved by $\Delta C = 7$. We emphasize that the abundance cannot be strongly constrained, due to a degeneracy in the continuum between the wind bremsstrahlung and contribution from the hot accretion flow (and/or a jet, if present) as represented by the power law.

Given the best-matching synthetic wind spectrum, the outflow rate of the hot wind can be evaluated according to the simulated density and radial velocity distributions. We find an outflow rate of $\sim 0.08 \text{ M}_\odot \text{ yr}^{-1}$. Interestingly, this value is comparable to the inflow rate of $0.07$–$0.2 \text{ M}_\odot \text{ yr}^{-1}$ estimated for warm ionized gas within the central $\sim 100$ pc traced by Hα emission (Schnorr-Müller et al. 2014). Theoretically, the hot wind is expected to carry away the bulk of the inflowing mass in the hot accretion flow (Yuan et al. 2015). The good agreement between the inferred outflow and inflow rates lends strong support to the wind scenario.

5. Discussion

5.1. Alternative Origins of the High-velocity Hot Plasma

5.1.1. Stellar Activities

In principle, the high-velocity Fe lines may be produced by stellar activities such as young supernova remnants (SNRs) or massive stellar binaries with strong colliding winds. However, the X-ray luminosity of the 16 keV plasma, $4 \times 10^{41} \text{ erg s}^{-1}$, is orders of magnitude higher than that possible for a single young SNR (Dwarkadas & Grusko 2012). Theoretical investigation (Rimoldi et al. 2016) also shows that the cumulative X-ray luminosity from a collection of SNRs evolving within the sphere of influence of a $\sim 10^8 \text{ M}_\odot$ SMBH ($\sim 100$ pc in radius) does not exceed $\sim 10^{38} \text{ erg s}^{-1}$. Similarly, colliding wind binaries cannot reach the observed X-ray luminosity and plasma temperature (Gagné et al. 2012).

To further evaluate the collective X-ray emission from the circumnuclear stellar populations, we first estimate the stellar mass and star formation rate (SFR) in the HETG spectral extraction region. The stellar mass within a projected radius of 265 pc is found to be $\sim 1 \times 10^4 \text{ M}_\odot$, based on the V-band surface brightness distribution of NGC 7213 (Lauer et al. 2005) and assuming a V-band mass-to-light ratio of 5.4 typical of an Sa galaxy (Faber & Gallagher 1979). The SFR is estimated to be $\lesssim 0.02 \text{ M}_\odot \text{ yr}^{-1}$, based on the measured luminosity of narrow Hα line from the nucleus of NGC 7213 (Filippenko & Halpern 1984) and the empirical relation between SFR and Hα luminosity (Kennicutt 1998). These estimates then provide an upper limit in the X-ray luminosity contributed by both old and young stellar populations, $L_{\text{X, SFR}} = \alpha M_\odot + \beta \text{SFR}$, where $\alpha = (9.05 \pm 0.37) \times 10^{39} \text{ erg s}^{-1} \text{ M}_\odot^{-1}$ and $\beta = (1.62 \pm 0.22) \times 10^{39} \text{ erg s}^{-1} (\text{ M}_\odot \text{ yr}^{-1})^{-1}$. This is orders of magnitude lower than the observed X-ray luminosity of the $16 \text{ keV}$ plasma. Moreover, the circumnuclear star formation is expected to produce a $0.5$–$2 \text{ keV}$ luminosity of $L_{\text{X, SFR}} = 9 \times 10^{37} (\text{ SFR}/0.02 \text{ M}_\odot \text{ yr}^{-1})^{-1} \text{ erg s}^{-1}$, based on the empirical relation of Ranalli et al. (2003). This is about two orders of magnitude lower than the observed X-ray luminosity of the low-T component (Section 3.3). Hence we conclude that stellar activities cannot account for the thermal components in the HETG spectrum.

5.1.2. AGN Photoionization

Alternatively, the highly ionized Fe lines may be produced by AGN photoionization. We evaluate this possibility using the photoionization code Cloudy (ver c17.02; Ferland et al. 2017). The code calculates the ionization state of an isotropic and uniform gas cloud photoionized by a central source, which has an intrinsic X-ray spectrum, $\phi(\nu)$, the same as the baseline power-law continuum (Section 3.1), i.e., with a photon-index of 1.723 and 0.5–10 keV luminosity of $2.4 \times 10^{42} \text{ erg s}^{-1}$. We note that the X-ray luminosity has varied by a factor of $\sim 4$ over a period of $\sim 38$ yr (Yan & Xie 2018), but our conclusion below is not affected by this moderate variability. The inner radius of the cloud is set to be 0.001 pc ($\sim 260 r_g$), while the outer radius varies with different assumed values of column density $N_c = n_c (r_{\text{out}} - r_{\text{in}})$, where $n_c$ is the cloud density assumed to be constant for simplicity. We note that adopting a radially decreasing density distribution does not significantly affect our conclusion. The ionization parameter at the illuminated face of the cloud is expressed by $U_X = \int_{2 \text{ keV}}^{10 \text{ keV}} \phi(\nu) \nu \, d\nu$. The lack of a reflection component in the broadband X-ray spectrum indicates a Compton-thin case. Hence we explore the plausible parameter space of $N_c = 10^{21}$–$10^{24} \text{ cm}^{-2}$ and ionization parameters $U_X = 1$–$7$. For a given set of $N_c$ and $U_X$, the outward luminosity of a certain atomic line is then calculated using the theoretical line emissivity from ATOMDB and assuming an abundance of twice solar, to be consistent with the favored abundance in the synthetic wind spectrum.
The predicted line luminosities are shown in Figure 10. We find that the predicted Fe XXVI Ly\(\alpha\) line from a photoionized cloud falls short by a factor of a few to a few hundred to the observed luminosity, for any reasonable combination of \(N_c\) and \(U_X\). The predicted Fe XXV K\(\alpha\) line is also typically weak and only comes closer to the observed luminosity at small values of \(U_X\). Therefore, the hot plasma traced by the highly ionized Fe lines is highly unlikely due to photoionization by the LLAGN.

We note that Bianchi et al. (2008) also disfavored an origin of photoionization for the Fe lines based on the argument that the resonant transition dominates the Fe XXV triplet. Line luminosities are also predicted for the three low-Z lines detected: Mg XII Ly\(\alpha\), Ar XVIII Ly\(\alpha\), and Ca XIX K\(\alpha\). Among them, the Mg XII Ly\(\alpha\) line can have a predicted luminosity comparable to the observed value, whereas the other two predicted lines typically fall short to the observed value except with the lowest \(U_X\). This suggests that photoionization by the LLAGN can at best account for a fraction of the low-Z lines.

5.1.3. The Hot Accretion Flow

In principle, the hot accretion inflow inside the truncation radius can also produce highly ionized Fe lines with a substantial Doppler shift. To test such a possibility, we utilize a set of 3D general relativity (GR) MHD simulations of the hot accretion flow with the Kerr metric performed with the Atheta ++ code (White et al. 2016). The simulation is scale-free in black hole mass; hence, we can scale the simulation data to \(M_{BH} = 10^8 M_\odot\). Although the 3D GRMHD simulation only extends from the event horizon to 100 \(r_g\), all physical quantities of the hot accretion flow, such as density, temperature, and velocity have a tight scaling relation in the radial direction, which allow us to extrapolate these quantities from 100 \(r_g\) to 2000 \(r_g\). An inflow rate of 0.08 \(M_\odot\) yr\(^{-1}\) at 2000 \(r_g\) is adopted to normalize the gas density, which is consistent with the derived outflow rate in the hot wind (Section 5.2).

We then follow the same procedure for the wind simulation to produce a synthetic spectrum of the hot accretion flow for a given line of sight. The Fe abundance is set to be twice solar. We find that within 1000 \(r_g\), the plasma temperature reaches \(>8 \times 10^9\) K, which is so high that the gas becomes fully ionized; the bulk of Fe XXV and Fe XXVI ions exist in the radial range of 1000–2000 \(r_g\), where the temperature drops to \(\sim 10^9\) K. However, the predicted equivalent width of the Fe XXVI Ly\(\alpha\) line is only \(\sim 15\) eV, much low than the observed value of 61.2 eV. Moreover, due to the wide spread of the projected velocity in this radial region, the resultant line profile takes a
broad and flat-topped shape, which is inconsistent with the observed narrow line profile. We also find it difficult to produce a large flux ratio as observed between the blueshifted and redshifted components, since the inflow itself is optically thin and is barely obscured by the truncated disk. These discrepancies between the synthetic and observed spectra persist for a number of viewing angles tested. Hence we conclude that the blueshifted highly ionized Fe lines are not originated from the hot accretion flow.

5.2. Comparison with M81* and Implications for LLAGN Feedback

In the previous sections, we have shown that the blueshifted lines from highly ionized Fe are best understood as arising from a hot wind launched from the hot accretion flow onto the SMBH in NGC 7213. A mass outflow rate of $\sim 0.08 M_\odot \, yr^{-1}$ is inferred for this hot wind (Section 5.2). We further estimate an associated kinetic power of $\sim 3 \times 10^{42} \, erg \, s^{-1}$. This is equivalent to $\sim 15\%$ of the SMBH’s bolometric luminosity (Yan & Xie 2018), a fraction very similar to that found for the hot wind in M81* (Shi et al. 2021). The momentum flux of the hot wind is estimated to be $\sim 4 \times 10^{33} \, g \, cm \, s^{-1}$, which is $\sim 6$ times the photon momentum flux from the LLAGN. This is again similar to the case of M81*. In view that M81* and NGC 7213 encompass a substantial range in the Eddington ratio ($3 \times 10^{-5} - 10^{-3}$), this similarity may suggest a quasi-universal mechanical output of the hot wind with respect to the SMBH’s radiative output, which deserves further examination when detection of the hot wind in more LLAGNs becomes available. In any case, the kinetic power and momentum flux of the hot wind can provide an efficient and long-lasting means of feedback from weakly accreting SMBHs that are prevalent in normal galaxies.

Among the crucial open questions about LLAGN feedback is whether the hot wind can deposit its kinetic energy and momentum into a substantial volume of the host galaxy, as required to effectively quench star formation in cosmological simulations (Weinberger et al. 2017; Pillepich et al. 2018). Numerical simulations predict that the hot wind will interact with the circumnuclear medium, releasing its kinetic energy and momentum and potentially creating strong shocks (Yoon et al. 2019). The 0.8 keV plasma found in the HETG spectrum might be evidence for such an interaction, which is likely the manifestation of a circumnuclear hot gas shock-heated by the outward propagating hot wind. We note that circumnuclear hot gas with a similar temperature is also evident in the case of M81* (Shi et al. 2021). The internal energy of this circumnuclear hot gas in NGC 7213 is $\lesssim 1 \times 10^{54} \, erg$, assuming that it fills a spherical volume with a radius of 265 pc (i.e., the HETG spectral extraction region). This translates to a reasonably short time of $\sim 1 \times 10^3 \, yr$ if the entire kinetic power of the hot wind were converted into this internal energy.

The hot wind could have propagated to larger distances from the LLAGN. The zeroth-order spectrum of the off-nucleus region examined in Section 3.4 allows for the presence of a 0.8 keV plasma out to $\sim 550$ pc, but with a substantially lower surface brightness. This may be understood as either the hot wind having been impeded and had the bulk of its kinetic power exhausted by the circumnuclear medium, or a paucity of gas in the off-nucleus region. Interestingly, recent Atacama Large Millimeter/submillimeter Array CO observations reveal the presence of nonrotating molecular gas features at distances of few hundred parsec from the nucleus (Salvestrini et al. 2020), which were interpreted as a molecular gas outflow with a velocity of $\lesssim 100 \, km \, s^{-1}$ and a mass outflow rate of $0.03 \pm 0.02 M_\odot \, yr^{-1}$. While Salvestrini et al. (2020) favored stellar activity as the mechanism responsible for the outflow, the possibility that this molecular gas is accelerated and entrained by the hot wind deserves further investigation.

At present, direct evidence for the hot wind from a weakly accreting SMBH is only found in M81* and NGC 7213. This may be attributed to two limiting factors. On the one hand, high-resolution X-ray spectra are currently only available for a handful of nearby LLAGNs (Appendix A). Among these sources, M81* and NGC 7213 stand out with better data quality to allow for the detection of highly ionized Fe lines. On the other hand, even with a deep X-ray spectrum, the presence of a strong X-ray continuum from a relativistic jet (e.g., in the case of Cen A and M87) may easily mask the emission lines. Future high-resolution X-ray spectroscopic observations by Chandra, as well as planned missions such as XRISM and Athena, hold promise to confirm the universality of a hot wind from LLAGNs.

6. Summary

We have searched the Chandra archive for ACIS/HETG observations of LLAGNs that may reveal potential evidence for a putative hot wind driven by a hot accretion flow and characterized by highly ionized iron lines, as recently established in the case of M81*. Only one source, the LLAGN in NGC 7213, manifests itself with X-ray spectral features similar to those found in M81*. We have performed an in-depth X-ray spectral analysis for NGC 7213, as well as MHD simulations of the hot wind tailored to the empirical conditions of the weakly accreting SMBH in this galaxy. Our main findings are as follows.

1. A blind search results in the detection of a number of emission lines from the Chandra 1st-order HEG/MEG spectra. In particular, Fe XXVI Ly$\alpha$ and Fe XXV Ka$\alpha$ lines with a blueshifted velocity of $\sim 1100 \, km \, s^{-1}$ are identified. The flux ratio between the two lines suggests that they are tracing a hot plasma with a characteristic temperature of $16 \pm 6 \, keV$. The spectra show no significant redshifted counterpart to this plasma. In addition, several emission lines from low-Z elements indicate the presence of a $\sim 0.8 \, keV$ plasma, which may be tracing a circumnuclear hot gas.

2. The synthetic X-ray spectrum of the hot wind from the MHD simulation with a viewing angle of $\sim 80^\circ$ and an Fe abundance twice solar can well match the blueshifted, highly ionized Fe lines. In this case, the unseen redshifted counterpart is most likely due to obscuration by the truncated disk along the line of sight. All plausible alternative origins considered for the Fe lines, such as stellar activity, AGN photoionization, and the hot accretion flow itself, are quantitatively disfavored. This makes a strong case that a hot wind exists in the nucleus of NGC 7213, presumably driven by the hot accretion flow.

3. The mass outflow rate of the hot wind is estimated to be $\sim 0.08 M_\odot \, yr^{-1}$, quite comparable to the inflow rate of...
ionized gas estimated for warm ionized gas within the central \( \sim 100 \) pc traced by H\(_\alpha\) emission. This agreement between the outflow and inflow rates lends further support to the hot wind scenario for NGC 7213.

4. The wind carries a kinetic energy of \( \sim 3 \times 10^{42} \) erg s\(^{-1}\) and a momentum flux of \( \sim 4 \times 10^{33} \) g cm s\(^{-1}\), thus providing an important means of kinetic feedback to the environment.

Future X-ray and optical spectroscopic observations in a spatially resolved fashion will be crucial to determining to what extent and at what efficiency the hot wind can affect the interstellar medium of the host galaxy.

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Software: CIAO (Fruscione et al. 2006), XSPEC (Arnaud 1996), NuSTARDAS (v1.9.2), ZEUS-MP/2 (v1.5.19; Hayes et al. 2006), Cloudy (vc17.02; Ferland et al. 2017), Atheta++ code (White et al. 2016).

Appendix A
Sample Selection

We examined publicly available Chandra ACIS/HETG observations of nearby LLAGNs for potential signatures for the putative hot wind. We found a total of 79 well-classified AGNs with existing ACIS/HETG observations. For these AGNs, we calculated the Eddington ratio, \( \lambda_{\text{Edd}} = \frac{L_{\text{bol}}}{L_{\text{Edd}}} \), where \( L_{\text{Edd}} = 1.26 \times 10^{38} \left( \frac{M_{\text{BH}}}{M_\odot} \right) \) erg s\(^{-1}\) is the Eddington luminosity. For sources without \( M_{\text{BH}} \) measurement in the literature, we assumed \( M_{\text{BH}} \geq 10^7 M_\odot \). We also assumed that the 2–10 keV X-ray luminosity, looked up from the literature, accounts for \( \sim 10\% \) of the bolometric luminosity \( L_{\text{bol}} \).

Among the 79 AGNs with ACIS/HETG observations, we classified 14 LLAGN candidates, which have \( \lambda_{\text{Edd}} \leq 10^{-3} \). We have downloaded and reprocessed the ACIS/HETG data of these 14 targets following the same procedures described in Section 2. Unfortunately, only one target, NGC 7213, exhibits clear evidence of emission lines from the H-like and He-like Fe, which are taken as a defining signature of the putative hot wind. The remaining 13 LLAGNs, including famous targets such as Cen A and M87, show no significant lines of highly ionized Fe. For reference, the HEG spectra of these 13 LLAGNs are shown in Figure A1.
Figure A1. The HEG spectra of 13 LLAGNs selected from the Chandra archive. The spectra are binned to have a signal-to-noise ratio greater than three for better illustration. The target name is provided in each panel.
Appendix B
Self-absorption of the Hot Wind to the Fe Lines

To verify that self-absorption of FeXXV Kα and FeXXVI Lyα lines in the hot wind can be neglected, we evaluate the optical depth (Rybicki & Lightman 1979), \( \tau(E) = \frac{N_i c^2 f_{lu}}{m_e c} \phi(E) \), along a typical line of sight, where \( N_i \) refers to the column density of a certain ion (here Fe XXV or Fe XXVI), \( f_{lu} \) is the oscillator strength of electron transition from lower level \( l \) to upper level \( u \), \( m_e \) is the electron mass, and \( c \) is the speed of light. The value of \( N_i \) as a function of temperature is obtained from ATOMDB. The iron abundance is chosen to be twice solar, along with an average hydrogen column density of \( \sim 6 \times 10^{22} \text{ cm}^{-2} \) from the wind simulation. The Voigt function \( \phi(E) \) is numerically solved for the projected gas velocity along the line of sight.

The resultant optical depth of the hot wind for photon energies between 6 and 7.5 keV is shown in Figure B1. It can be seen that in the vicinity of the FeXXV Kα and FeXXVI Lyα lines, the optical depth is typically \( \lesssim 0.1 \) and always \( \lesssim 0.37 \). We conclude that our assumption of negligible self-absorption in the hot wind is adequate.

![Figure B1. The optical depth of the hot wind as a function of photon energy between 6 and 7.5 keV (black curve), for a viewing angle of 80°. The two peaks are due to Fe XXV Kα and Fe XXVI Lyα. Self-absorption is only moderate in both lines.](image-url)
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