The Variable Relativistic Outflow of IRAS 13224–3809

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Abstract

The discovery of an ultrafast outflow has been reported in the $z=0.0658$ narrow-line Seyfert galaxy IRAS 13224–3809. The ultrafast outflow was first inferred through the detection of highly blueshifted absorption lines and then confirmed with a principal component analysis. Two of the reported properties of this outflow differed from those typically detected in other AGNs with ultrafast outflows. First, the outflow velocity was found not to vary with $v = 0.236c \pm 0.006c$. Second, the equivalent width of the highly blueshifted absorption line was reported to be anticorrelated with the $3–10$ keV flux of this source. We present a reanalysis of the XMM-Newton observations of IRAS 13224–3809 considering the influence of background. We also undertook a different analysis approach in combining the spectra and investigated the change of the properties of the outflow as a function of $3–10$ keV flux and time. We confirm the presence of an ultrafast outflow in IRAS 13224–3809; however, we find that the background spectra used in the Parker et al. analyses dominate the source spectra for energies near the blueshifted iron lines. By reducing the source extraction regions to improve the signal-to-noise ratio, we discover larger than previously reported outflow velocities and find that the outflow velocity varies from $\sim 0.2c$ to $\sim 0.3c$ and increases with $3–10$ keV flux. The previously reported anticorrelation between equivalent width of the iron line and $3–10$ keV flux disappears when the background spectra are reduced by optimizing the source extraction regions.

Key words: black hole physics – galaxies: Seyfert – X-rays: galaxies

1. Introduction

Relativistic wide-angle outflows of active galactic nuclei (AGNs) are now considered one of the main mechanisms regulating the evolution of galaxies through a feedback process (see, e.g., review by King & Pounds 2015 and references therein). These wide-angle winds are thought to transfer a substantial amount of their kinetic energy to the surrounding gas, resulting in quenching of star formation in the host galaxy by heating the interstellar medium (ISM) or by ejecting the gas from the galaxy (e.g., Faucher-Giguère & Quataert 2012, Zubovas & King 2012). Several of these models consider two main phases of the interaction between the wind and the ISM. In the momentum-conserving phase the relativistic wind collides with the ISM, producing a forward- and reverse-shocked wind that loses a significant amount of its kinetic energy through inverse Compton cooling. In the energy-conserving phase the wind expands adiabatically and reaches a terminal velocity of a few thousand kilometers per second. The first evidence of powerful relativistic winds in quasars came from observations of APM 08279+5255, PG 1211+143, and PDS 456 (Chartas et al. 2002; Pounds et al. 2003; Reeves et al. 2003). Follow-up studies of a larger sample of nearby Seyfert galaxies showed that about 40% of these AGNs have highly ionized ultrafast outflows (UFOs) with velocities exceeding 10,000 km s$^{-1}$ and with average velocities ranging between $0.1c$ and $0.3c$ (Tombesi et al. 2010; Gofford et al. 2013). There have been attempts to compare the energetics of small-scale UFOs with larger-scale molecular outflows in galaxies to test feedback models. The presence of both small- and large-scale energy-conserving outflows was recently discovered by Tombesi et al. (2015) in the $z=0.189$ ULIRG IRAS F11119+3257 and by Feruglio et al. (2015) in the $z=0.04217$ ULIRG Mrk 231. Feruglio et al. (2017) have also reported the detection of molecular gas outflowing with maximum velocity of $v = 1340$ km s$^{-1}$ in the UFO/BAL quasar APM 08279+5255 at $z=3.912$.

Recently, Parker et al. (2017a) reported the discovery of a relativistic wind in the $z=0.0658$ narrow-line Seyfert galaxy IRAS 13224–3809. The discovery was based on the analysis of XMM-Newton observations of IRAS 13224–3809 made in 2016. These observations had a total exposure time of $\sim 1.5$ Ms spread over a month from 2016 July 8 to 2016 August 9. In their results they report the detection of multiple absorption features in the X-ray spectra. They interpret one of these absorption features, detected at an observed-frame energy of $E = 8.6$ keV, as originating from absorption by highly ionized iron outflowing with a speed of $0.236c \pm 0.006c$. They report that the velocity of this wind does not vary with luminosity and time and the equivalent width (EW) of the absorption feature is anticorrelated to the $3–10$ keV flux (see Figure 3 of Parker et al. 2017a). The $v$ versus $L_X$ and EW versus $F_X$ reported behavior of IRAS 13224–3809 appears to be very different from that detected in other luminous AGNs such as $z=3.91$ APM 08279+5255 (Chartas et al. 2002, 2009; Saez & Chartas 2011), $z=0.184$ PDS 456 (Nardini et al. 2015; Matzeu et al. 2017; Reeves et al. 2018), $z=0.062$ PG 1126–041 (Giustini et al. 2011), and $z=2.7348$ HS 1700+6416 (Lanzuisi et al. 2012). The relativistic outflow velocities detected in these AGNs have been reported to vary with time and in some instances with luminosity. A correlation has been found between the outflow velocity and the X-ray luminosity in APM 08279+5255 and PDS 456 (see Figure 10 in Saez & Chartas 2011 and Figure 3 in Matzeu et al. 2017), suggesting that radiative driving may be contributing to the acceleration of these winds. Parker et al. (2017b) independently analyzed the variability of IRAS 13224–3809 using principal component analysis (PCA). They report the detection of significant spectral variability at energies similar to the ones found in their previous spectral analysis.
Table 1
Log of Observations of IRAS 13224–3809

| Date       | OBS ID       | Exposure (s) | Net Exp. (s) | Net Count Rate (s⁻¹) | $f_{3-10}$ a |
|------------|--------------|--------------|--------------|-----------------------|--------------|
| 2016 Aug 09 | 0792180601   | 134,915      | 121,283      | 3.817 ± 0.006         | 7.86 ± 0.10  |
| 2016 Aug 07 | 0792180501   | 136,306      | 120,248      | 1.544 ± 0.004         | 4.19 ± 0.10  |
| 2016 Aug 03 | 0792180401   | 139,717      | 124,604      | 3.810 ± 0.006         | 8.52 ± 0.13  |
| 2016 Aug 01 | 0792180301   | 139,417      | 120,431      | 0.715 ± 0.003         | 2.34 ± 0.10  |
| 2016 Jul 30 | 0792180201   | 139,414      | 125,938      | 1.788 ± 0.004         | 3.60 ± 0.09  |
| 2016 Jul 26 | 0792180101   | 139,919      | 127,435      | 1.518 ± 0.004         | 3.34 ± 0.10  |
| 2016 Jul 24 | 0780561701   | 139,715      | 125,831      | 1.406 ± 0.003         | 3.15 ± 0.07  |
| 2016 Jul 22 | 0780561601   | 139,711      | 127,405      | 2.880 ± 0.005         | 5.75 ± 0.10  |
| 2016 Jul 20 | 0780561501   | 139,716      | 127,743      | 1.220 ± 0.003         | 2.66 ± 0.07  |
| 2016 Jul 12 | 0780561401   | 137,015      | 80,172       | 2.221 ± 0.005         | 4.82 ± 0.09  |
| 2016 Jul 10 | 0780561301   | 139,918      | 123,883      | 1.884 ± 0.004         | 3.92 ± 0.09  |
| 2016 Jul 08 | 0780560101   | 140,219      | 31,396       | 1.705 ± 0.007         | 3.27 ± 0.09  |

Notes.
a Date of exposure start.
b Time is the effective exposure time remaining after the application of good time interval tables and the removal of portions of the observation that were severely contaminated by background flaring.
c Background-subtracted source counts including events with energies within the 0.4–10 keV band. The source counts and effective exposure times for the XMM-Newton observations refer to those obtained with the EPIC-pn instrument. The radii of the circular source and background extraction regions are 600 and 1600 pu, respectively.
d The 3–10 keV flux of the $r_{600}$ spectra in units of $10^{-13}$ erg s⁻¹ cm⁻².

In Section 2 we present the X-ray observations and data reduction of IRAS 13224–3809. In Section 3 we apply PCA to IRAS 13224–3809 following the methodology described in Parker et al. (2017b). In Section 4 we search for possible variability of the outflow velocity as a function of flux and time. In Section 5 we present our results on the dependence of the EW of the iron absorption line with the 3809 keV. In Section 3 we apply PCA to the EW of the iron absorption line with the 3809 keV. In Section 6 we present a summary of our conclusions.

Throughout this paper we adopt a flat Λ cosmology with $H_0 = 68$ km s⁻¹ Mpc⁻¹, $Ω_Λ = 0.69$, and $Ω_M = 0.31$ (Planck Collaboration et al. 2016).

2. X-Ray Observations and Data Reduction

In Table 1 we list the observation dates, exposure times, background-subtracted source count rates, and 3–10 keV fluxes of IRAS 13224–3809. For the present analysis we are mostly concerned with examining the properties of absorption features with energies above 0.5 keV. In this energy range the EPIC-pn has superior effective area to the two MOS detectors combined. We therefore concentrated our effort on the reduction and analysis of the EPIC-pn data of IRAS 13224–3809 alone.

For the reduction of the XMM-Newton observations we filtered the EPIC-pn (Strüder et al. 2001) data by selecting events corresponding to instrument PATTERNS in the 0–4 range (single- and double-pixel events). Several moderate-amplitude background flares were present during several of the XMM-Newton observations. The EPIC-pn data were filtered on a rate of <20 counts s⁻¹, using the SAS task tabgtigen, to exclude times when these flares occurred, resulting in the effective exposure times listed in Table 1. To test for sensitivity to background nonuniformity, we also tried different background extraction regions. We did not find any differences in the spectral shapes and features using more conservative threshold cuts or selecting different background extraction regions. The EPIC-pn spectra were binned to have at least 20 counts per bin, as appropriate for fitting spectra using χ² statistics.

The EPIC-pn observations of IRAS 13224–3809 were performed in Large Window mode to reduce the effects of pileup. The “tolerant” EPIC-pn flux limit threshold for Large Window mode is 6 counts s⁻¹ (Jethwa et al. 2015). According to this study, the fractional flux loss in Large Window mode and for soft spectra with maximum photon rates of 6 counts s⁻¹ is ∼6%. For the purpose of estimating the effects of pileup we calculated the count rates over the entire energy band of the EPIC-pn for circular source extraction regions with radii of 700 pu. The maximum EPIC-pn count rates of spectra stacked by flux and by time in our analysis are 5.7 and 4.08 counts s⁻¹, respectively. Spectra stacked by flux and time have count rates below the “tolerant” EPIC-pn flux limit threshold for Large Window mode, and therefore flux loss and spectral distortion due to pileup effects are negligible in our analysis. Moreover, IRAS 13224–3809 has a soft spectrum, and the effects of pileup are expected to be reduced at energies above ∼2 keV. Parker et al. (2017a) also investigated the effects of pileup for these EPIC-pn observations of IRAS 13224–3809 and did not find any spectral distortion above 2 keV in this soft X-ray source. We conclude that pileup does not affect the results of our analysis, especially in the 3–10 keV band, where we have detected absorption lines from the UFO.

3. PCA of IRAS 13224–3809

We reanalyzed the 2016 XMM-Newton observations of IRAS 13224–3809 using PCA as described in Parker et al. (2017b) to check whether we could reproduce their published results. We tested the sensitivity of the reduction of the IRAS 13224–3809 data to the size and location of the background and source extraction regions. We also investigated the level of background at energies near the reported absorption features in both individual (used in the PCA analysis) and stacked spectra.
We select circular source extraction regions of two different radii, \( r = 250 \) and 600 \( \text{pn} \) physical units (\( \text{pu}, 1 \text{pu} = 0.05\) ), centered on IRAS 13224–3809 and circular background regions of \( r = 1600 \text{pu} \), making sure that the background extraction regions were outside of the elevated Cu background ring region of the EPIC-pn. The source extraction region of \( r = 600 \text{pu} \) was selected to compare with the results published in Parker et al. (2017a). Specifically, Parker et al. (2017a) show their source and background regions in their Extended Data Figure 2 marked by small and large white circles, respectively. From their Extended Data Figure 2 and the known angular size of the EPIC-pn CCDs, we infer that the source and background diameters of their extractions regions are 60'' and 120'', respectively. We also determined the 0.3–10 keV light-curves of IRAS 13224–3809 for extraction regions of diameter 60'' to compare with the 0.3–10 keV light curve presented in the Extended Figure 1 of Parker et al. (2017a). We reproduce the same count rates as in their Extended Figure 1 when using 60''-diameter circular extraction source extraction regions.

We selected a source extraction region of \( r = 250 \text{pu} \) to optimize the signal-to-noise ratio (S/N) in the 8–10 keV region, which contains the detected blueshifted Fe XXV and Fe XXVI resonance absorption lines. The percent decrease in the background-subtracted source counts in the 0.4–10 keV band obtained by using \( r = 250 \text{pu} \) extraction region compared to the 600 \text{pu} \) region is about 20%. However, the background of spectra extracted from the 250 \text{pu} \) regions is reduced by a factor of \( \sim 6 \) compared to spectra extracted using the 600 \text{pu} \) regions. A more detailed justification of the selection of the \( r = 250 \text{pu} \) source extraction regions is provided later on in Section 4.

We employed the \textit{XMM-Newton} science analysis system tool \texttt{arfgen} with enabled encircled energy correction for point sources to create the ancillary response files (arf) appropriate for each selected source extraction region.

Observations were divided into increments of \( t = 10 \text{ks} \) to match the intervals used in the Parker et al. (2017b) analysis, and pn source and background spectra were extracted for each 10 ks interval. For the pn data reduction we used SAS software version 16.1.

The background-subtracted spectra were rebinned into equal logarithmic bins in energy, and the PCA analysis was performed for a range of fractional bin widths. The 10 ks spectra were stored in a matrix \( f(t_j, E_i) \), where the \( n \) columns are the energies \( E_i \) of the spectral bins and the \( m \) rows are the times \( t_j \) of the 10 ks intervals.

The average spectrum over all \( m \) 10 ks intervals was computed as

\[
 f_{\text{ave}}(E_i) = \frac{\sum_{j=1}^{m} f(t_j, E_i)}{m}. \tag{1}
\]

The normalized variation of a spectrum from the average spectrum \( f_{\text{ave}} \) was calculated as

\[
 f_{\text{var}}(t_j, E_i) = \frac{f(t_j, E_i) - f_{\text{ave}}(E_i)}{f_{\text{ave}}(E_i)}. \tag{2}
\]

Using the IDL routine \texttt{SVDC}, we computed the singular value decomposition of the \( m \times n \) matrix \( f_{\text{rad}}(t_j, E_i) \) as the product of an \( (m \times n) \) orthogonal array \( A \); an \( (n \times n) \) diagonal array \( \text{SV} \), composed of the singular values; and the transpose of an \( (n \times n) \) orthogonal array PC:

\[
 f_{\text{var}} = (A)(\text{SV})(PC)^T. \tag{3}
\]

The spectral variability as a function of energy is stored in the principal components \( PC(i, E_i) \), where most of the variability of the source is stored in the first component \( PC(1, E_i) \). The contributions of principal components to each 10 ks spectrum are stored in the light curves \( A(i, t_j) \):

\[
 f_{\text{var}}(t_j, E_i) = \sum_{i=1}^{n} A(i, t_j)PC(i, E_i). \tag{4}
\]

Parker et al. (2017a) stacked spectra that fell within a defined range of 0.3–10 keV count rates and determined the 3–10 keV flux of each stacked spectrum. We initially followed this approach by stacking spectra as a function of count rates (see Table 2) to compare results, but we also adopted a slightly different approach in selecting how to stack spectra. Specifically, we determined the individual 3–10 keV fluxes of each 10 ks spectrum, stacked spectra that fell within a defined range of 3–10 keV fluxes, and determined the 3–10 keV flux of each stacked spectrum. We chose this approach since count rates and 3–10 keV fluxes are not exactly proportional in the presence of spectral variability. This is shown in Figure 1, where we show a plot of total count rates versus 3–10 keV fluxes for all 10 ks spectra of IRAS 13224–3809. Considerable scatter between 3 and 10 keV fluxes and 0.3–10 keV count rates is evident. We conclude that the inferred 3–10 keV fluxes of stacked spectra that were combined based on their total count rates do not accurately represent the fluxes of the stacked spectra.

We next investigated the sensitivity of the reported PCA results on IRAS 13224–3809 to background. The first eigenvector component \( PC(1, E) \) from PCA obtained from data extracted from circular source extraction regions of \( r_{\text{ext}} = 600 \text{pu} \) (300”) and \( r_{\text{ext}} = 250 \text{pu} \) (125.5”) radii is presented in Figure 2. We confirm the enhanced spectral variability at energies similar to the ones reported in Parker et al. (2017b). The only difference is a slight increase of \( PC(1, E) \) for energies above observed-frame energies of 8 keV, when background contamination is reduced.

### 4. Variability of the Outflow of IRAS 13224–3809

#### 4.1. Variability of Outflow as a Function of 3–10 keV Flux

In Figure 3 we plot the combined EPIC-pn spectra of IRAS 13224–3809 extracted from circular source extraction regions of \( r_{\text{ext}} = 600 \text{pu} \) (referred to as \( r_{600} \) spectra) and overplot the background spectra. The spectra were combined in six flux regimes based on their 0.3–10 keV fluxes listed in the panels of Figure 3.

We find that the background begins to dominate at observed-frame energies above \( \sim 7.5 \) keV. In Figure 3 we also plot the same spectra of IRAS 13224–3809, but extracted from circular source regions of \( r_{\text{ext}} = 250 \text{pu} \) (referred to as \( r_{250} \) spectra). The background in all flux levels for the \( r_{250} \) spectra is significantly reduced compared to the \( r_{600} \) spectra.

To justify the selection of an extraction region of \( r_{\text{ext}} = 250 \text{pu} \), we show in Figure 4 the S/Ns in the 8–10 keV region of IRAS 13224–3809 for source extraction regions of 150, 250, 500, 600, and 700 \text{pu} \) and background subtraction regions of \( r = 1600 \text{pu} \). The S/Ns were calculated for combined spectra of IRAS 13224–3809 with 3–10 keV fluxes of less than \( 2 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \), the lowest
Clear residual features are detected in the stacked range of 3–11 keV count rates. The horizontal dashed lines indicate the boundaries of the flux ranges selected for stacking spectra.

Table 2

| Count-rate Regimes | Count Rate \( f_{10} \) (s\(^{-1}\)) | \( f_{10} \times 10^{−13} \text{erg s}^{-1} \text{cm}^{-2} \) |
|--------------------|---------------------------------|---------------------------------|
| 1                  | 0–0.6                           | 1.65±0.06                       |
| 2                  | 0.6–0.95                        | 2.95±0.07                       |
| 3                  | 0.95–1.4                        | 3.36±0.18                       |
| 4                  | 1.4–1.95                        | 4.85±0.12                       |
| 5                  | 1.95–2.3                        | 5.75±0.27                       |
| 6                  | 2.3–3.2                         | 7.53±0.16                       |
| 7                  | >3.2                            | 10.04±0.22                      |

Notes.

a The count rates are calculated in the 0.3–10 keV observed-frame energy band of IRAS 13224–3809.
b \( f_{10} \) are the 3–10 keV fluxes of the combined \( r_{600} \) spectra of IRAS 13224–3809 of each count-rate regime.

3–10 keV flux range shown in Figure 3. A significant improvement in the S/Ns of the spectra in the 8–10 keV range is achieved by selecting extraction regions of \( r_{600} = 250 \text{ pu} \) compared to \( r_{600} = 600 \text{ pu} \). In Figure 4 we also plot the ratios of the pn effective area using \( r = 150, 250, 500, \) and 600 pu source extraction regions to that of an \( r = 700 \text{ pu} \) source extraction region. We note that the effective-area ratios are smooth functions across the 8–10 keV observed-frame energy range.

We conclude that modeling the EPIC-pn spectra of IRAS 13224–3809 extracted from circular source extraction regions of \( r_{\text{ext}} = 250 \text{ pu} \) will likely result in unreliable results, especially for features detected above observed-frame energies of \( \sim 7 \text{ keV} \). To illustrate the presence of possible emission and/or absorption features, we fit the stacked \( r_{250} \) spectra of IRAS 13224–3809 with a simple absorbed power-law model. Clear residual features are detected in the stacked \( r_{250} \) spectra of IRAS 13224–3809 (see Figures 3 and 5).

Guided by these residual features, we next fit the stacked \( r_{250} \) spectra with a simple absorbed power-law model that contains one or two absorption lines and up to two emission lines. Since we are only interested in constraining the high-energy absorption features, we restricted the spectral fits to the energy range of 3–11 keV. The 68%, 90%, and 99% confidence contours of the rest-frame energies of the detected absorption lines versus their line strengths are shown in Figure 5. Only absorption lines detected at the \( >99\% \) confidence level are presented in this figure. Significant high-energy absorption features are detected in all flux ranges. The energies of the absorption lines vary with 3–10 keV flux ranging between rest-frame energies of \( 8.64±0.05 \text{ keV} \) and \( 9.96±0.09 \text{ keV} \). As we show later on in this section, these absorption lines are likely the result of absorption by highly ionized iron (Fe XXV and Fe XXVI).

We followed a more robust approach of estimating the significance of the blueshifted absorption iron lines based on Monte Carlo simulations to determine the distribution of the \( F \)-statistic between different models (Protassov et al. 2002). Following this approach, for each spectrum we simulated 1000 data sets using the XSPEC fakeit command (Arnaud 1996). We considered a null model that included a simple absorbed power law and an alternative model that in addition included one or two Gaussian absorption lines. We fit the 1000 data sets with the null and alternative models and determined the distribution of the \( F \)-statistic\(^1\) from these fits. Finally, we computed the probability for the \( F \) value to exceed the value determined from the fits of the null and alternative models to the observed spectra. The Monte Carlo simulations indicate that the shifted iron lines are detected at \( >99\% \) confidence in all flux levels and confirm the significance of the detections calculated using \( \chi^2 \) confidence contours. In Table 3 we present the energies and the significance of the iron absorption lines detected in IRAS 13224–3809 as a function of the 3–10 keV flux of the \( r_{250} \) spectra that were combined in selected ranges of fluxes shown in Figure 1.

4.2. Variability of Outflow as a Function of Time

We also investigated the variability of the outflow as a function of time. In Figure 6 we show the light curve of the

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\(^1\) The \( F \)-statistic is given by \( F = \frac{\chi_{\text{obs}}^2 - \chi_{\text{mod}}^2}{\Delta \nu} / \frac{\chi_{\text{mod}}^2}{\nu} \).
3–10 keV flux of IRAS 13224–3809. We selected seven consecutive time intervals to study the evolution of the outflow and combined the EPIC-pn $r_{250}$ spectra in these intervals. The selection of the time intervals in our time-resolved spectroscopic analysis was based on the following criteria. We chose consecutive time intervals with similar S/N spectra to allow for spectral fitting using photoionization codes. We also selected time intervals that isolated large flares. Specifically, in several of these intervals significant flares are evident where the 3–10 keV flux varies by a factor of ~2 in a timescale as short as 10 ks, which is consistent with a light-crossing-time size of less than ~300$r_g$, where $r_g = G M_{BH}/c^2$ and $M_{BH} \sim 6 \times 10^9 M_\odot$ is the black hole mass of IRAS 13224–3809 reported in Zhou & Wang (2005). The published values of the black hole mass of IRAS 13224–3809 show modest differences based on the method used to estimate them. For example, by measuring the accretion disk flux, Chiang et al. (2015) obtained $M_{BH} = 3.5^{+0.5}_{-0.6} \times 10^6 M_\odot$, whereas reverberation analysis presented in Emmanoulopoulos et al. (2014) reports $M_{BH} = 9.3^{+3.4}_{-2.9} \times 10^6 M_\odot$.

In Figure 7 we show the residuals between a fitted model and the spectra in the 6–11 keV observed-frame energy range. The model used to produce these residuals is a simple absorbed power-law model. We verified that the background spectra lie below all the stacked $r_{250}$ source spectra for energies below ~10 keV. The reduced background of the $r_{250}$ spectra allows for reliable identifications of the high-energy absorption lines.

We find significant variability of the energy and velocity of the outflow of IRAS 13224–3809.

In order to determine the energies and significance of the absorption lines in the seven time intervals, we fit the $r_{250}$ spectra of IRAS 13224–3809 with a model that consists of a simple absorbed power law, a Gaussian absorption line, and one or two emission lines. In Table 4 we present the energies and the significance of the iron absorption lines detected in IRAS 13224–3809 for the seven time intervals shown in Figure 6. The most significant change of the outflow velocity of IRAS 13224–3809 is observed between intervals $t_5$ and $t_7$. In Figure 8 we show a typical example of the Monte Carlo simulated distribution of the $F$-statistic between fits of the null and alternative models to the observed spectra of IRAS 13224–3809 obtained during intervals $t_5$ and $t_7$. The blueshifted lines in these time intervals are detected at >99.9% confidence.

We also searched for changes of the energies of possible soft X-ray absorption lines by fitting the full-band 0.5–10 keV EPIC-pn spectra of the time intervals $t_5$ and $t_7$ that showed the most dramatic variability of the energies of the Fe absorption lines. The model fit to the full energy band was similar to the one used in the Pinto et al. (2018) analysis. Specifically, we used a model that consists of Galactic absorption, intrinsic cold absorption, a blackbody to account for the soft excess, a power law for the direct emission, a relativistically blurred reflected emission component, and X-ray transmission through a photoionized gas. For the relativistically blurred X-ray
reflection we used the RELXILL model (Dauser et al. 2014; García et al. 2014). We use the analytic XSTAR model warmabs (Kallman & Bautista 2001) to model the transmission of the outflowing intrinsic ionized absorber.

The fit with this model shows no significant features between 1.5 and 10 keV except for the Fe XXV/Fe XXVI lines; however, several broad residual features are present between 0.5 and 1.5 keV. The origin of these broad residual features is uncertain; however, these features may result from modeling the soft excess with a simple blackbody. Other plausible candidates for these broad residual include pileup that is known to distort spectra and will be more significant at energies below \( \sim 2 \) keV, and the presence of multiple outflowing components of various ionization states.

4.3. Correlation between Outflow Velocity and 3–10 keV Flux

We searched for a possible dependence between the outflow velocity and the 3–10 keV flux in the seven time intervals shown in Figure 6. The line energies listed in Table 3 and obtained from fitting the \( r_{250} \) spectra with a model that consisted of a simple absorbed power law and one or two Gaussian absorption lines were converted to outflow velocities. Specifically, for the conversion we used the relativistic Doppler formula assuming that the high-energy absorption lines are the result of resonance absorption from ions of Fe XXVI in a gas with solar abundances, and the angle between our line of sight and the outflow direction is zero. In Figure 9 we show that a trend exists, with the outflow velocity increasing with 3–10 keV flux. We fit a null hypothesis model of a constant behavior between velocity and flux and find \( \chi^2 = 113 \) for 6 degrees of freedom (\( \nu \)). The probability \( P_{\nu}(\chi^2/\nu) \) of exceeding \( \chi^2 = 113 \) for \( \nu = 6 \) is \( P_{\nu}(113; 6) < 1 \times 10^{-15} \). We conclude that the null hypothesis model of a constant behavior between velocity and flux is rejected at a very high significance level.

\[
\nu_{\text{wind}} = \left[ \left( \frac{f_{\text{bol}}}{L_{\text{Edd}}} - 1 \right) \left( \frac{1}{R_{\text{launch}}} - \frac{1}{R} \right) \right]^{1/2},
\]

where \( \nu_{\text{wind}} \) is the outflow velocity in units of \( c \), \( \Gamma_f \) is the force multiplier, \( L_{\text{bol}} \) and \( L_{\text{Edd}} \) are the bolometric and Eddington
luminosities, respectively, $R_{\text{launch}}$ is the radius (units of $R_3$) at which the wind is launched from the disk, and $R$ is the distance (units of $R_3$) from the central source.

We fit the outflow velocity versus 3–10 keV luminosity of IRAS 13224–3809 with the function $v_{\text{wind}} = aL^{b}$ to compare the observed trend with Equation (5). We find a best-fit value of $b = 0.40 \pm 0.03$ with a $\chi^2/\nu = 1.3$. A fit with a straight line results in a significantly worse fit with $\chi^2/\nu = 1.7$. The best-fit value of $b = 0.40 \pm 0.03$ would imply that radiation driving may be contributing to the acceleration of this wind; however, there are several concerns with this interpretation that we describe later on in this section. We note that a similar trend was found in PDS 456 with a best-fit value of $b = 0.20 \pm 0.05$. The best-fit model $v_{\text{wind}} = aL^{b}$ fit to the outflow velocity versus 3–10 keV luminosity of IRAS 13224–3809 is shown in Figure 9.

Pinto et al. (2018) reported a tentative correlation between the outflow velocity and the luminosity of IRAS 13224–3809 based on modeling spectra stacked by count-rate levels and extracted from circular regions with $r = 600$ pu. The highly ionized iron line, however, is not detected in their analysis to shift with luminosity, and they find the strength of the iron absorption line to decrease with luminosity. Pinto et al. (2018) conclude that the UFO disappears in high-radiation fields. We have shown that the $r_{600}$ spectra of IRAS 13224–3809 are background dominated above $\sim 7$ keV (see Figure 3) and that the analysis of the $r_{250}$ spectra of IRAS 13224–3809, which are not background dominated, clearly shows the increase in the energies of the Fe XXV and Fe XXV lines with increasing 3–10 keV flux. As we show in Section 5, the EW of the Fe line does not decrease with luminosity when analyzing the $r_{250}$ spectra of IRAS 13224–3809, and the UFO, as manifested in the blueshifted highly ionized iron lines, does not vanish in the high-radiation fields. One possible reason these shifts of the Fe line were not detected previously is that in the high flux states the Fe lines shift into even more background-dominated parts of the $r_{600}$ spectra of IRAS 13224–3809.

It has been suggested that similar correlations found in APM 08279+5255 and PDS 456 may indicate that radiation pressure is contributing to the acceleration of the wind since the terminal velocity of a radiatively driven wind scales as $v_{\infty} \propto \sqrt{\Gamma fL}$, where $\Gamma f$ is the force multiplier of the outflowing absorber. However, there are some problems with the premise that the main acceleration mechanism for these relativistic winds is radiation driving. Specifically, the launching radii inferred from the large relativistic outflow velocities of $\lesssim 100 r_g$, indicate that only a fraction of the UV-emitting region of the accretion disk will be contributing to radiation driving at these radii. Moreover, the terminal velocity of the outflowing wind depends on the force multiplier, which decreases with increasing ionization parameter. As shown in Figure A.6 of Saez & Chartas (2011) for the best-fit values of the ionization parameters found in IRAS 13224–3809, the force multiplier is calculated to be close to 1, implying that radiation driving, at least near the launching site, is not a main contributor to the acceleration of the wind. Finally, the 3–10 keV luminosity of AGNs is a relatively small fraction of the bolometric luminosity, and the central X-ray flux alone cannot accelerate the wind to the observed speeds, resulting in the calculated efficiencies that we find for IRAS 13224–3809 and that are presented at the end of this section.

We next proceed with fitting the spectra of the intervals $t_f$ and $t_r$ to determine the properties of the outflowing absorber and search for possible changes of the absorber properties over a period of $\sim 500$ ks. Guided by the shape and location of identified absorption and emission residuals (see Figure 7), we fit the spectra of intervals $t_f$ and $t_r$ with a model that consists of a power law modified by Galactic absorption, an outflowing intrinsic ionized absorber, and relativistically blurred X-ray reflection from parts of the accretion disk near the black hole. We attempt to mimic the velocity broadening of the absorption lines by introducing in the XSTAR $\text{warmab}$ model turbulent velocities. We performed several fits using $\text{warmab}$ where we allowed the turbulence velocity to vary and found best-fit values of $v_{\text{turb}} \sim 5500$ km s$^{-1}$ for interval $t_f$ and $v_{\text{turb}} \sim 1500$ km s$^{-1}$

| $f_{10}$ | $E_{\text{abs}}$ | EW$_{\text{abs}}$ | $N_{\text{abs}}$ | $\chi^2$ | $v$ | $C$ | $P_{10}$ | $P_{25}$ |
|---------|-----------------|-----------------|-----------------|--------|-----|-----|---------|---------|
| 0.14    | 0.14            | 0.14            | 0.14            | 0.14   | 0.14| 0.14| 0.14    | 0.14    |
| 0.15    | 0.15            | 0.15            | 0.15            | 0.15   | 0.15| 0.15| 0.15    | 0.15    |
| 0.16    | 0.16            | 0.16            | 0.16            | 0.16   | 0.16| 0.16| 0.16    | 0.16    |
| 0.17    | 0.17            | 0.17            | 0.17            | 0.17   | 0.17| 0.17| 0.17    | 0.17    |
| 0.18    | 0.18            | 0.18            | 0.18            | 0.18   | 0.18| 0.18| 0.18    | 0.18    |
| 0.19    | 0.19            | 0.19            | 0.19            | 0.19   | 0.19| 0.19| 0.19    | 0.19    |
| 0.2     | 0.2             | 0.2             | 0.2             | 0.2    | 0.2 | 0.2 | 0.2     | 0.2     |
| 0.21    | 0.21            | 0.21            | 0.21            | 0.21   | 0.21| 0.21| 0.21    | 0.21    |
| 0.22    | 0.22            | 0.22            | 0.22            | 0.22   | 0.22| 0.22| 0.22    | 0.22    |
| 0.23    | 0.23            | 0.23            | 0.23            | 0.23   | 0.23| 0.23| 0.23    | 0.23    |
| 0.24    | 0.24            | 0.24            | 0.24            | 0.24   | 0.24| 0.24| 0.24    | 0.24    |
| 0.25    | 0.25            | 0.25            | 0.25            | 0.25   | 0.25| 0.25| 0.25    | 0.25    |

Notes. These properties were obtained from fits to the $r_{250}$ spectra of IRAS 13224–3809 combined in the 3–10 keV flux ranges indicated in Figure 3.

The 3–10 keV flux of the $r_{250}$ spectra (combined by 3–10 keV flux) listed in Figure 3 in units of $10^{-13}$ erg s$^{-1}$ cm$^{-2}$.

Rest-frame energies of the blueshifted Fe absorption lines.

Rest-frame EW of the blueshifted Fe absorption lines.

Normalization of the blueshifted Fe absorption line in units of $10^{-7}$ photons cm$^{-2}$ s$^{-1}$.

Degrees of freedom of alternative mode. The $\chi^2$ of the null model is quoted in parentheses.

Degrees of freedom of alternative mode. The degrees of freedom of the null model are quoted in parentheses. The null model includes a simple absorbed power law, and the alternative model includes one or two Gaussian absorption lines.

$\chi^2$ confidence detection levels of the blueshifted Fe absorption lines.

$P_{10}$-statistic between the null and alternative models.

The probability of exceeding this $F$ value as determined from the Monte Carlo simulations.
for interval $t_7$. The spectral fits were performed in the 2–10 keV observed-frame energy range to avoid the soft excess at lower energies and to focus on the blueshifted absorption lines in this range. The default atomic population file `pops.fits` provided in NASA’s `warmabs` distribution uses a fixed value of the photon index of $\Gamma = 2$. However, our spectral analysis indicates that the 2–10 keV photon index $\Gamma$ increased from $\sim 2.0$ to $\sim 2.4$ between intervals $t_5$ and $t_7$. We therefore used XSTAR to create new population files appropriate for photon indices of the spectra of intervals $t_5$ and $t_7$. The best-fit values for the column density, ionization parameter, and outflow velocity of the wind from fitting this model to the spectra of intervals $t_5$ and $t_7$ are presented in Table 5. We find a significant change in outflow velocity from $v = 0.173^{+0.006}_{-0.008} c$ to $v = 0.283^{+0.006}_{-0.006} c$ within a period of about 500 ks. The velocities derived from the XSTAR photoionization model (listed in Table 5) are consistent, within errors, with the velocities derived from the spectral fits using Gaussian absorption lines and show a similar trend with flux. We note that the outflow velocities derived from fits to the $r_{250}$ spectra using the `relxill + warmabs` model are not as sensitive (as compared to fitting Gaussian lines, for example) to the assumed ionization state.

In Figure 10 we show the unfolded best-fit photoionization plus relativistic reflection models to the spectra of intervals $t_5$ and $t_7$ in the region near the blueshifted Fe XXV and Fe XXVI absorption lines. The spectral evolution of the wind is evident between intervals $t_5$ and $t_7$. The best-fit photoionization models to the $r_{250}$ spectra of intervals $t_5$ and $t_7$ are shown in Figure 11. Variability of the direct and reflected components and the increase in outflow velocity are evident. Since Fe absorption lines were also detected at $>$99% confidence in time intervals $t_3$ and $t_5$, we fit the spectra of IRAS 13224–3809 in these intervals with the model that consists of a power law modified by Galactic absorption, an outflowing intrinsic ionized absorber, and relativistically blurred X-ray reflection. The properties of the outflow for time intervals $t_1$ and $t_3$ are also included in Table 5. In Figure 12 we present the $r_{250}$ spectra of IRAS 13224–3809 in the time intervals $t_1$, $t_3$, $t_5$, and $t_7$, in which we have detected the Fe absorption line at $\geq 99.9\%$ confidence. We overplot the best-fit model that consists of a power law modified by Galactic absorption, an outflowing intrinsic ionized absorber, and relativistically blurred X-ray reflection. We also overplot the background spectra to show that the detected Fe absorption lines are not affected by background. The $r_{250}$ stacked spectra clearly show the variability of strength and energy of the Fe line and show that the Fe line is detected at the high-ionization levels as well (see Table 5).

The observed variability of the energies of the absorption lines is likely to have contributed to the broadening of the peaks of the eigenvector component $PC(1,E)$ shown in Figure 2. We searched for possible variability of component...
These properties were obtained from Notes.

The time intervals used to extract the spectra of IRAS 13224−3809 are shown in Figure 6.

The 3−10 keV flux of the IRAS spectra (combined by 3−10 keV flux) listed in Figure 3 in units of ×10^{-13} erg s^{-1} cm^{-2}.

Rest-frame energy of the blueshifted Fe absorption lines.

Rest-frame EW of the blueshifted Fe absorption lines.

Normalizing the blueshifted Fe absorption line in units of ×10^{-7} photons cm^{-2} s^{-1}.

A confidence detection level of the blueshifted Fe absorption lines.

The degrees of freedom of the null model are quoted in parentheses.

The degrees of freedom of the null model are quoted in parentheses.

The probability of exceeding this F value as determined from the Monte Carlo simulations.

The significance of several of the soft X-ray PC(1, E) peaks for the individual time intervals t1 through t7 is relatively low, and we focus our discussion on the two most significant PCA peaks around ~3 and ~8 keV. The significance of these two peaks varies between ~1σ and 4σ based on the errors derived from our Monte Carlo analysis. We find significant variability of the energies and the relative strengths of these peaks in the PC(1, E) component; however, the peaks do not all vary in the same manner between time intervals. For example, the PC(1, E) peak near the observed-frame energy of 3 keV (which is likely associated with S XVI) does not vary in energy between time intervals t2 and t7; however, the PC(1, E) peak near the observed-frame energy of 8 keV (which is likely associated with Fe XXV/Fe XXVI) varies significantly in energy between t2 and t7. This may imply the presence of multiple components in the outflow with different outflow properties. Another reason for the different behaviors of the PCA peaks between time intervals is that the ionization parameter and density of the outflow may be varying, leading to the presence of different atomic absorption lines in each time interval.

The second-largest outflow velocity of ν = 0.283 ± 0.006c detected in time interval t7 was found to be significant at >99.9% confidence with Monte Carlo simulations (Figure 8), with the Fe XXV absorption line showing three data points significantly below the continuum and the Fe XXVI absorption line showing four data
points significantly below the continuum (Figures 7 and 12). The largest ionization of log $\xi$ (erg cm s$^{-1}$) = 5.15$^{+0.20}_{-0.25}$, inferred in time interval $t_1$, was found for an absorption line detected to be significant at $\sim$99.8% confidence with Monte Carlo simulations (see Table 4). The two highest flux states (detected at $>99.9\%$ confidence) of $f_{310}$ = 5.79$ \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $f_{210}$ = 4.79$ \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ were detected in time intervals $t_2$ and $t_1$, respectively. We conclude that the relativistic outflow in IRAS 13224−3809 does not disappear at the highest flux and/or ionization levels, in contrast to what was concluded using a background-dominated spectra in previous studies (e.g., Parker et al. 2017b; Pinto et al. 2018). On the contrary, the weakest detection ($\sim$98% confidence) of the Fe line is made in time interval $t_4$ which has the lowest flux level of $f_{310}$ = 2.35$ \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$.

One important assumption when stacking spectra either by flux or by time is that the properties of the absorber ($N_{HI}$, $\xi$, $v_{outflow}$, ionizing SED) and reflector have not varied significantly. As shown in Figures 3 and 6, the $r_{250}$ spectra stacked by flux show multiple absorption features in the 8–11 keV range within a single stacked spectrum. On the other hand, as shown in Figures 7 and 12, spectra stacked by time contain well-defined Fe absorption lines and, when fit with the relxill + warmabs model, provide acceptable fits in a statistical sense. As shown in Figure 6, the 3–10 keV flux of IRAS 13224−3809 changes by factors of up to $\sim$8 in time interval $t_2$ and by $\sim$2 in 10 ks. If the velocity of the outflow was tracking the short-timescale variations of the 3–10 keV flux, then one would expect to find multiple absorption lines smeared between 0.2c and 0.3c in the stacked by time interval $r_{250}$ spectra. But this is not what we observe. On the other hand, the $r_{250}$ spectra stacked by flux do show multiple components as expected for spectra stacked with different outflow properties.

5. EW of Fe Absorption Line versus 3–10 keV Flux of IRAS 13224−3809

In Figure 14 we show the EW of the high-energy absorption lines as a function of the 3–10 keV flux obtained from modeling the stacked (based on their 0.3–10 keV count rates) $r_{250}$ and $r_{600}$ spectra of IRAS 13224−3809. Specifically, spectra with 0.3–10 keV count rates that lie within specific ranges listed in Table 2 were stacked, and the 3–10 keV flux of the each stacked spectrum was calculated. As we show in Figure 1, there is significant scatter between the 0.3 and 10 keV count rates and the 3–10 keV fluxes of IRAS 13224−3809; however, we present these results to directly compare with results presented in Parker et al. (2017a). We fit the EW versus 3–10 keV flux data with a straight-line of slope $a$. For the fits obtained from modeling the stacked $r_{250}$ and $r_{600}$ spectra (based on their 0.3–10 keV count rates) we find slopes of $a = -0.03 \pm 0.15$ and $a = -0.35 \pm 0.11$, respectively.

In Figure 15 we show the EW of the high-energy absorption lines as a function of the 3–10 keV flux obtained from modeling the stacked (based on their 3–10 keV fluxes) $r_{250}$ and $r_{600}$ spectra of IRAS 13224−3809. The flux ranges used to stack spectra are shown in Figures 1 and 3. For the fits to the EW versus 3–10 keV data obtained from modeling the stacked $r_{250}$ and $r_{600}$ spectra (based on their 0.3–10 keV fluxes) we find slopes of $a = -0.1 \pm 0.1$ and $a = -0.46 \pm 0.14$, respectively.

We reproduce within errors the anticorrelation of the EW versus 3–10 keV flux found by Parker et al. (2017a) when performing a spectral analysis of the high-background stacked $r_{600}$ spectra of IRAS 13224−3809 both for stacking based on 0.3–10 keV count rates and for stacking based on 3–10 keV fluxes. More importantly, however, we find that when analyzing the stacked $r_{250}$ spectra of IRAS 13224−3809, which are less affected by background than the $r_{600}$ spectra, the anticorrelation disappears, with the best-fit slopes being consistent with zero within errors. We conclude that we find no significant dependence of the EW of the high-energy absorption lines with 3–10 keV flux in IRAS 13224−3809. Another relevant point comes from Section 4, where we found that the energy and strength of the iron absorption lines are variable. Modeling spectra stacked according to their 3–10 keV fluxes is therefore likely to lead to unreliable and unrealistic results.

Pinto et al. (2018) performed simultaneous fits to the count-rate-selected full-band EPIC-pn and RGS spectra of IRAS 13224−3809 and suggested (see their Figure 3) that the absorption lines weaken and seem to disappear at higher luminosities. We have demonstrated that the highly ionized Fe absorption lines do not disappear at higher luminosities when
The Astrophysical Journal, 867:103 (14pp), 2018 November 10
Chartas & Canas

Table 5
Properties of the Outflow of IRAS 13224—3809

| Time Interval | \( N_w \) \( \times 10^{24} \text{ cm}^{-2} \) | \( \log \xi \) \( \text{(erg cm s}^{-1}\text{)} \) | \( v_{\text{obs}} \) \( \text{(c)} \) | \( M \) \( (\text{M}_\odot \text{ yr}^{-1}) \) | \( \epsilon_K \) |
|---------------|----------------------------------|----------------------------------|-----------------|-----------------|-----------------|
| \( t_1 \)     | \( 0.74^{+0.58}_{-0.35} \)       | \( 5.15^{+0.20}_{-0.25} \)      | \( 0.226^{+0.005}_{-0.007} \) | \( 0.45^{+0.43}_{-0.30} \) | \( 0.19^{+0.18}_{-0.12} \) |
| \( t_3 \)     | \( 0.62^{+0.17}_{-0.26} \)       | \( 4.5^{+0.20}_{-0.25} \)       | \( 0.194^{+0.005}_{-0.005} \) | \( 0.3^{+0.23}_{-0.19} \)   | \( 0.10^{+0.07}_{-0.07} \)  |
| \( t_5 \)     | \( 1.0^{+0.5}_{-0.6} \)          | \( 3.7^{+0.1}_{-0.1} \)         | \( 0.173^{+0.005}_{-0.005} \) | \( 0.47^{+0.31}_{-0.31} \)   | \( 0.11^{+0.07}_{-0.07} \)  |
| \( t_7 \)     | \( 0.13^{+0.09}_{-0.06} \)       | \( 4.3^{+0.3}_{-0.3} \)         | \( 0.283^{+0.006}_{-0.006} \) | \( 0.10^{+0.07}_{-0.07} \)   | \( 0.06^{+0.04}_{-0.04} \)  |

Notes. The properties of the outflow were determined by fitting a model that consists of a power law modified by Galactic absorption, an outflowing intrinsic ionized absorber, and relativistically blurred X-ray reflection to the \( r_{250} \) spectra of IRAS 13224—3809.

The best-fit value of the column density of the outflowing absorber obtained by fitting the \( r_{250} \) spectra of IRAS 13224—3809 with the warmabs photoionization model.

The efficiency of the outflow, \( \epsilon_K \), is defined as the ratio of the outflow mechanical luminosity to the bolometric luminosity of IRAS 13224—3809.

Figure 10. Unfolded spectra and and best-fit photoionization models to the IRAS 13224—3809 \( r_{250} \) spectra of intervals \( t_5 \) (top) and \( t_7 \) (bottom). The inferred outflow velocities of the absorber for intervals \( t_5 \) and \( t_7 \) are \( v = 0.17^{+0.005}_{-0.006} c \) and \( v = 0.283^{+0.006}_{-0.006} c \), respectively.

Figure 11. Best-fit photoionization models to the IRAS 13224—3809 \( r_{250} \) spectra of intervals \( t_5 \) (top) and \( t_7 \) (bottom). The black and red dotted lines indicate the direct and reflected components, respectively. The blueshifted resonance spectral lines of Ne X, Fe XXIV, Si XIV, S XVI, Fe XXV, and Fe XXVI are indicated in red.

outflowing absorber and accretion disk are the same for similar count-rate levels over a \( \sim 4 \) yr period.

6. Energetics of the Relativistic Outflow of IRAS 13224—3809

Two important properties of an AGN’s outflow that may indicate whether or not it is important in regulating the growth of the host galaxy are the mass outflow rate (\( M \)) and the ratio of the rate of kinetic energy ejected by the outflow to the AGN’s bolometric luminosity (\( \epsilon_K \)):

\[
\epsilon_K = \frac{1}{2} \frac{M v^2}{L_{\text{bol}}}, \quad \text{where} \quad M = 4\pi R^2 \rho v_c = 4\pi f_c \frac{R^2 N_{\text{H}} m_p v}{\Delta R},
\]

where \( f_c, N_{\text{H}}, R, \) and \( \Delta R \) are the covering fraction, column density, radius, and thickness of the outflowing absorber, respectively. We estimated \( M \) and \( \epsilon_K \) for the two time intervals \( t_5 \) and \( t_7 \) for which a significant change in the outflow velocity background is reduced in the EPIC-pn spectra. The Pinto et al. spectral results may have been affected in the simultaneous fits since their EPIC-pn spectra are background dominated above \( \sim 7 \) keV and the inferred properties of the outflowing ionized absorber for their full-band fits may be unreliable. The only significant soft X-ray features in their EPIC-pn count-rate stacked spectra lie in the range of 0.5–1 keV. The origin of these features is uncertain and may be partly due to modeling the soft excess with a simple blackbody component. There are additional assumptions made in the Pinto et al. analysis that may have affected their spectral results. For example, the line width and the line-of-sight velocity of the outflowing absorber are fixed and tied in their spectral fits to the measured values of Parker et al. (2017a), whereas our analysis shows that these quantities vary significantly. In addition, the spectra in the Pinto et al. analysis have been combined by count rate over a \( \sim 4 \) yr period. Their analysis assumes that the properties of the
is observed, and the iron absorption lines are detected at >99.9% confidence.

The global covering factor of the outflow absorber is not constrained with the current observations. Specifically, there is no strong P Cygni profile detected in any of the spectra of IRAS 13224–3809. Several broad emission features detected between the observed energies of ~7 and ~8 keV are likely associated with the relativistic Fe line from the accretion disk. We assume a covering factor $f_c$ lying in the range of 0.3–0.6 based on the detected fraction of UFOs in Seyfert galaxies (e.g., Tombesi et al. 2010, Gofford et al. 2013). To estimate the launching radius, we assume that the maximum observed outflow velocity is produced by gas that has reached its terminal velocity, resulting in the approximation $R_{\text{launch}} \sim \frac{R_s (c/\nu_{\text{wind}})^2}{\nu_{\text{wind}}}$, where $\nu_{\text{wind}}$ is the observed outflow velocity and $R_s = 2GM/c^2$. For estimating the mass outflow rate and outflow efficiency, we assumed a fraction $R/\Delta R$ ranging from 1 to 10 based on theoretical models of quasar outflows (e.g., Proga et al. 2000). We used a Monte Carlo approach to estimate the errors of $\dot{M}$ and $\epsilon_k$. In Table 5 we list the mass outflow rate and the efficiency of the outflow for time intervals $t_1$, $t_3$, $t_5$, and $t_7$. The mass outflow rates for time intervals $t_5$ and $t_7$ that are separated by ~500 ks are $\dot{M} = 0.47_{-0.40}^{+0.54} M_\odot \ yr^{-1}$ and $\dot{M} = 0.20_{-0.17}^{+0.22} M_\odot \ yr^{-1}$, respectively, which are comparable to the accretion rate of IRAS 13224–3809, which we estimate to be $1.8 \times 10^{-3} (L_{44}/\eta) M_\odot \ yr^{-1} \sim 0.6 M_\odot \ yr^{-1}$, where we assumed a typical accretion efficiency of $\eta = 0.1$. We estimate the outflow efficiencies for time intervals $t_5$ and $t_7$ to be $\epsilon_k = 0.11_{-0.07}^{+0.10}$ and $\epsilon_k = 0.06_{-0.04}^{+0.04}$, respectively. For comparison purposes we note that Parker et al. (2017a) report a mass outflow rate of $\dot{M} = 0.03 \Omega M_\odot \ yr^{-1}$, where $\Omega$ is the solid angle of the wind. For their estimate, they assumed that the properties of the absorber did not vary over the ~1-month observing period of IRAS 13224–3809. Specifically, they assumed for their estimate of $\dot{M}$ an ionization state of Fe XXV, a launching radius of 8 pc, a constant wind velocity of 0.244 $c$, a column density of $8 \times 10^{22} \ cm^{-2}$, and a ratio of the distance of the absorber from the black hole to the absorber thickness of $r/\Delta r = 1$. Our estimated mass outflow rates differ from the Parker et al. (2017a) reported value based on our revised analysis of the EPIC-pn observations of IRAS 13224–3809. Specifically, our estimates of the energetics of the wind of IRAS 13224–3809 are based on fitting photoionization models to the time-resolved $r_{250}$ spectra that show significant variability of the properties of the wind. Our mass outflow rates listed in Table 5 range between 0.1 and 0.47 $M_\odot \ yr^{-1}$, assuming a covering fraction lying in the range of 0.3–0.6.

Our estimated ratios of the outflow mechanical luminosities to the bolometric luminosity, albeit with large uncertainties, are large enough, according to numerical simulations (Di Matteo et al. 2005;
Hopkins & Elvis (2010; Zubovas & King 2012), for the outflow to unbind gas in the bulge of the host galaxy if this energy were efficiently transferred to the ISM.

7. Conclusions

We have presented results from a reanalysis of XMM-Newton observations of IRAS 13224–3809 to assess the influence of background on previously reported results. We also undertook a slightly different analysis approach in combining the spectra and investigated the change of the properties of the outflow as a function of 3–10 keV flux and time. The main conclusions of our spectral and timing analyses are the following:

1. We confirm by applying PCA on the $r_{250}$ and $r_{600}$ spectra of IRAS 13224–3809, taken from the total exposure time of $\sim$1.5 Ms spread over a month from 2016 July 8 to 2016 August 9, the presence of significant variability of the spectrum of IRAS 13224–3809 at rest-frame energies of 1.33, 1.81, 2.51, 3.20, 4.40, 5.38, 6.06, and 8.57 keV. These energies are similar to the ones reported in Parker et al. (2017b). The significance of these individual peaks in the combined spectrum of IRAS 13224–3809 lies in the range of $1\sigma$-$4\sigma$, as indicated by the thickness of the shaded regions of the eigenvector PC(1, $E$) shown in Figure 13 as derived from our Monte Carlo analysis. The only difference is a slight increase of PC(1, $E$) for energies above observed-frame energies of 8 keV, when background contamination is reduced when using the $r_{250}$ spectra (see Figure 2).

2. We find that at energies above $\sim$7 keV background contamination is significant (see Figure 3) for the source extraction regions used by Parker et al. (2017a, 2017b). When the background contamination in the spectral analysis is reduced by a factor of $\sim$6, by selecting smaller source extraction regions, we find several results that differ from the ones previously reported. Specifically, we do not find a constant velocity $v = 0.236 \pm 0.009c$ outflow in IRAS 13224–3809 as reported in Parker et al., analyzing the same data. Instead, we find that the energy
of the high-energy absorption line detected at >99.9% confidence increases with 3–10 keV flux, indicating an outflow with a velocity varying between v ∼ 0.2c and v ∼ 0.3c. (see Figures 7, 9, and 10)

3. PCA is a powerful tool in identifying spectral variability of the strengths of absorption lines. We applied time-resolved PCA to seven sequential time intervals of IRAS 13224–3809 to search for variability of the energies of the lines. We find significant variability of the energies and the relative strengths of the peaks of the PC(1, E) component; however, the peaks do not all vary in the same manner between time intervals (see Figure 13). Possible reasons for the difference in the behavior of the PCA peaks are the presence of multiple components in the outflow and variability of the column density and/or ionization parameter of the outflowing absorber.

4. We find that the EW of the iron absorption line detected in IRAS 13224–3809 is not anticorrelated with 0.3–10 keV flux when background levels are reduced using the r250 spectra. We find that the apparent anticorrelation is an artifact of background contamination.

5. With the reanalysis of the IRAS 13224–3809 spectra we have discovered higher than previously reported velocity components of the outflow, which is important in estimating the energetics of the outflow. In two time intervals labeled t2 and t1 (see Figure 6) of observations of IRAS 13224–3809 separated by about 500 ks we estimate that the mass outflow rate lies in the range of $M = 0.47^{+0.40}_{-0.31} - 0.10^{+0.09}_{-0.07} M_\odot$ yr$^{-1}$, which is comparable to the accretion rate of IRAS 13224–3809. In the same time intervals we find that the fraction of kinetic to bolometric luminosity lies in the range of $\epsilon_k = 0.11^{+0.10}_{-0.07} - 0.06^{+0.06}_{-0.04}$, suggesting that this wind produces significant feedback to the host galaxy.

It is difficult to detect such high-velocity outflowing components in nearby AGNs owing to the relatively low effective area of current X-ray observatories at energies above 8 keV. In high-redshift quasars, the iron absorption lines are redshifted to lower energies and are more easily detected, which may partly explain the discovery of the highest outflow velocities in distant quasars.

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