Detection of a possible multiphase ultra-fast outflow in IRAS 13349+2438 with NuSTAR and XMM-Newton

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ABSTRACT
We present joint NuSTAR and XMM-Newton observations of the bright, variable quasar IRAS 13349+2438. This combined dataset shows two clear iron absorption lines at 8 and 9 keV, which are most likely associated with two layers of mildly relativistic blueshifted absorption, with velocities of ~ 0.14c and ~ 0.27c. We also find strong evidence for a series of Lyα absorption lines at intermediate energies in a stacked XMM-Newton EPIC-pn spectrum, at the same blueshift as the lower velocity iron feature. This is consistent with a scenario where an outflowing wind is radially stratified, so faster, higher ionization material is observed closer to the black hole, and cooler, slower material is seen from streamlines at larger radii.

Key words: galaxies: active – accretion, accretion disks – black hole physics

1 INTRODUCTION
Since the launch of Chandra and XMM-Newton in 1999, astronomers have observed blueshifted absorption lines from highly ionized iron in the 7–10 keV energy range (e.g. Pounds et al. 2003; Chartas et al. 2002) of active galactic nuclei (AGN) X-ray spectra. These are usually interpreted as evidence for mildly relativistic (0.1–0.3c) winds, launched from the black hole accretion disk before crossing the line of sight to the X-ray source.

Because we can only see the effect of the absorption along the line of sight, it is hard to establish the structure of the absorbing gas. Typically, we only observe absorption lines from a single ionization state and velocity, often only a single Fe xxv/xxvi line. However, if we can detect more ionization states and velocities for a given UFO, we can start to infer some of the structure of the gas.

To date, only a small number of sources have robust (i.e. confirmed with multiple instruments, including NuSTAR) simultaneous detections of multiple ionization states of blueshfted absorption, notably PDS 456 (Reeves et al. 2018) and MCG-03-38-007 (Braito et al. 2018; Matzeu et al. 2019). The prevailing interpretation of these dual line detections is that they represent different streamlines in an outflowing wind, with more ionized, faster material coming from smaller radii.

IRAS 13349+2438 is a 10^9 M⊙ low redshift (z = 0.10853 Lee et al. 2013) quasar, which shows a high degree of X-ray variability (Ponti et al. 2012), and two layers of warm absorption, outflowing with velocities of ~ 600 km s⁻¹ (Sako et al. 2001). In 2018, using stacked archival XMM-Newton spectra of this source, we detected blueshifted lines of Si, S and Fe, with a velocity of ~0.13c (Parker et al. 2018b). We also saw weak, possibly background-dependent evidence for a second, more blueshifted Fe absorption line, but we were unable to confirm the detection. In this letter, we present new observations of IRAS 13349+2438 with XMM-Newton and NuSTAR, focusing on the detection of blueshifted absorption lines in the EPIC-pn and NuSTAR spectra.

2 OBSERVATIONS AND DATA REDUCTION
We were awarded a 200 ks NuSTAR exposure, simultaneous with a 100 ks XMM-Newton exposure, with a primary goal of determining whether the faster absorption feature was genuine. The combination of these two observatories is uniquely powerful detecting UFO lines: combining the high sensitivity and resolution of the EPIC instruments with the high-energy coverage of NuSTAR, which gives reliable measurements of the continuum shape.

The NuSTAR exposures were split into two: the first 50 ks was taken simultaneously with the XMM-Newton observation, and the remaining 150 ks taken two weeks later. There is little variability between the NuSTAR spectra of the two exposures (the 10–50 keV fluxes are 1.5 × 10⁻¹² and 1.6 × 10⁻¹² erg cm⁻² s⁻¹, respectively),
likely because of the high black hole mass and because AGN are generally less variable at high energies.

2.1 NuSTAR

The NuSTAR data were reduced using the NuSTAR Data Analysis Software (NuSTARDAS) version 1.9.2 and CALDB version 20200510. We extracted source photons from a 30' circular region centered on the source coordinates, and background photons from a larger ∼ 100' circular region on the same chip, avoiding contaminating sources, the chip gap, and the wings of the source PSF. We bin the FPMA and FPMB spectra to oversample the instrumental resolution by a factor of 3, and to a minimum signal to noise of 6 after background subtraction. The spectra from the two epochs are extremely similar, so we use a time-averaged NuSTAR spectrum for the remainder of the letter. For plotting purposes, we group the FPMA and FPMB spectra, but they are fit separately in all cases.

2.2 XMM-Newton

We reduced the XMM-Newton data using the Science Analysis Software (SAS) version 18.0.0 and the latest current calibration files (CCFs) at the time of writing. We extracted source photons from a 20' circular region centered on the source coordinates, and background photons from a larger circular region on the same chip. The EPIC-MOS detectors have higher background contamination at high energies, so are not useful for detecting the potential second Fe feature (the primary UFO features have already been confirmed with the MOS spectra: Parker et al. 2018b). We therefore restrict our analysis to the high signal EPIC-pn data.

The EPIC-pn was operated in small window mode, which excludes the regions of the chip with high copper contamination which can cause spurious features around 8 keV. We binned the spectra to a signal to noise ratio of 6, and to oversample the resolution by a factor of 3.

We also construct a stacked EPIC-pn spectrum with the addition of archival XMM-Newton data as well as the new observation. At high energies (>7 keV) this spectrum is not reliable and shows sharp features below the resolution limit of the detector. This is likely due to combining spectra from different epochs with different levels of background contamination and instrumental gain shift. We therefore restrict our analysis of this stacked spectrum to the lower energy band, where these effects are minimal.

3 RESULTS

In this work, we focus on the detection of UFO lines and defer detailed modelling of the continuum and warm absorbers for future analysis. For this reason, we only consider the spectra above 1 keV, and do not include the RGS data which is dominated by the effect of warm absorption. We have undertaken a preliminary inspection of the RGS spectrum to confirm that the absorption is close enough to that found in the archival data that we can safely stack the spectra together and assume the same warm absorption model in our fitting.

We find some moderate variability in the new observations, however a preliminary analysis shows minimal change in spectral shape associated with this variability, so for this work we use the time-averaged spectra. A full analysis of the variability properties will be presented in future work.

3.1 High energy spectrum

A simple inspection of the 2020 XMM-Newton EPIC-pn and NuSTAR FPMA/B data shows a clear pair of Fe absorption lines at ∼ 8 and ∼ 9 keV (Fig. 1, top). These correspond to the UFO we detected in Parker et al. (2018b) and the possible secondary feature that we discussed but were unable to confirm. As well as the average NuSTAR spectrum, the line is present in both NuSTAR exposures. The simultaneous detection of this feature with three instruments and in two different epochs leaves little ambiguity - it cannot be due to the XMM background, or noise. This feature must be either be due to a second layer of absorption, distinct in ionization and velocity from the primary absorber, or it is a higher order line from the primary absorber.

There is also a clear broad emission feature around 6–7 keV. In Parker et al. (2018b) we investigated the origin of this feature, comparing relativistic reflection with a P-Cygni profile. The reflection model gave a significantly better fit (ΔC-stat = 58, for 2 additional degrees of freedom), and a fit with both models combined implied that the majority of the line emission is due to disk reflection. However, the model used for the P-Cyg profile is a relatively simple phenomenological model, so it is possible that a more sophisticated model would give a better fit. We will explore this in more detail in a follow-up paper (Matzeu et al., in prep). For this work, we focus on the reflection interpretation, which gives a superior fit to the continuum.

Fitting the joint NuSTAR and XMM-Newton spectrum above 3 keV with a relativistic reflection continuum, modelled with relxilllp (García et al. 2014), and two Gaussian lines gives energies of 7.91 ± 0.05 keV and 9.26 ± 0.06 keV for the two lines, consistent with the ratio of 1.18 between the Fexxxvi Lyα and Lyβ lines. However, the equivalent width of the higher energy line is very high for the Lyβ, 2/3 the equivalent width of the Lyα line. We therefore consider it more likely that this represents an separate layer of absorption, and is probably due to highly ionized material that only produces Fexxxvi absorption. The lines themselves are highly significant: the improvement in fit for adding Gaussians to fit the 8 and 9 keV features is ΔC-stat= 112 and ΔC-stat= 40, respectively.

We next replace the two Gaussian absorption lines with two layers of highly ionized absorption, using the xabs model from xspec (Kaastra et al. 1996; Steenbrugge et al. 2003), converted to an xspec table model1 (for the procedure used to generate this model, see appendix of Parker et al. 2019). The xabs tables used here assume the default xspec ionization curves, from Steenbrugge et al. (2005), and solar abundances. The ionization values returned from this model will be slightly biased by using the assumed SED (for IRAS 13224-3809, the main effect was to bias log(ε) by +0.5.

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1 available from www.michaelparker.space/xspec-models.
3.2 Intermediate energy lines

To investigate the lower-velocity UFO further we use the stacked EPIC-pn spectrum, constructed from all the XMM-Newton exposures, to search for lower energy lines. When fitting this region of the spectrum, we include the two layers of warm absorption identified by Sako et al. (2001), with parameters fixed at the values from Parker et al. (2018b). We performed a preliminary inspection of the 2020 RGS spectrum to check that the absorption is consistent with that in earlier observations. There are some minor differences,
which we will examine in future work, but these are negligible at the resolution of the EPIC-pn.

We show the residuals of the 1–6 keV spectrum, fit with a phenomenological double power-law plus warm absorption, in Fig. 2, with the strongest high-ionization absorption lines at a velocity of 

-0.13 c labelled. There is a clear pattern of broad dips, corresponding to the Lyα lines of Ne to Ca and the Fexxiv triplet (rest frame energy $\sim$ 1.1 keV).

Individually, the statistical improvement from fitting these lines is relatively small (with the notable exception of the strong Sixxiv line), but collectively the significance is very high. We test this by adding a single layer of xabs absorption to the power-law continuum. This improves the fit by AC-stat=47, to C-stat/dof of 131/113, for four additional degrees of freedom, a cumulative detection significance of over 5σ.

To check that these features are not an artefact of the stacking process, we plot the same residuals for each EPIC-pn spectrum individually (Fig. 2, bottom). While the data are too noisy above 3 keV for lines to be identified, the lower energy lines are clearly present and consistent with each other between observations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Top: Residuals to a power-law model for the intermediate energy combined EPIC-pn spectrum from all observations of IRAS 13349+2438. Vertical lines indicate the Lyα lines blueshifted by a velocity of 0.13c. Bottom: The same residuals for each observation individually, showing the consistent Ne, Mg, and Si lines. Above 3 keV the data is too noisy and lines cannot be distinguished.}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|}
\hline
Model & Parameter & Value & Description/unit \\
\hline
xabs & $\log(\xi)$ & 3.9 $\pm$ 0.1 & Ionization (erg cm$^{-1}$) \\
$N_{\text{HI}}$ & & 1.8 $\pm$ 0.7 & Column (10$^{24}$ cm$^{-2}$) \\
$V_{\text{rms}}$ & $< 9000$ & 2D RMS velocity (km s$^{-1}$) \\
$\nu_{\text{out}}$ & 0.132 $\pm$ 0.006 & Outflow velocity (c) \\
\hline
power1aw1 & $\Gamma$ & 1.69 $\pm$ 0.06 & Photon index \\
 & norm & 9.8 $\pm$ 1 & $10^{-4}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$ \\
power1aw2 & $\Gamma$ & 4 $\pm$ 1 & Photon index \\
 & norm & 4 $\pm$ 1 & $10^{-4}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$ \\
\hline
C-stat/dof & 131/113 & Fit statistic \\
\hline
\end{tabular}
\caption{Best-fit parameters for UFO absorption applied to a phenomenological double power-law model from 1–6 keV.}
\end{table}

\section{4 DISCUSSION}

We consider it highly likely that the intermediate energy lines found in the stacked EPIC-pn spectrum and the slower of the two Fe absorption lines found in the high energy NuSTAR/EPIC-pn spectrum are from the same material. The parameters of the absorption used to fit the intermediate energy lines are within 1σ error of those of the slower absorption found in the high energy spectrum.

\subsection{4.1 Origin of the second Fe line}

The second Fe absorption feature, located at a rest-frame energy 9 keV, must be due to either absorption from Fextxvi in an additional layer, the Fextxvi Kβ line, associated with the 0.14c absorption, or a combination of the two, which is the scenario implicitly assumed in our double-absorption model.

We consider a pure Kα line unlikely, as the line is very strong relative to the Kσ line, roughly twice the expected 1:3 ratio (Krause & Oliver 1979). The observed ratio could be modified by the absorption having a covering fraction less than unity, in which case the stronger Kσ line would drop in equivalent width more than the Kβ line, however we find that a statistically better fit is obtained with two absorption layers than a single layer, even if that layer is allowed to partially cover the source (which can affect the Kσ/Kβ ratio).

We conclude that a combination of the Kβ line from the first layer of absorption and the Kσ line from a second layer of absorption is likely the reason for the 9 keV feature, although we cannot be completely sure, as more complex models that we have not considered may be able to produce a stronger Kβ feature.

\subsection{4.2 Dynamics}

Assuming that both layers of absorption are due to an outflowing wind, we can make approximate estimates of their relative locations and the amount of power in each layer. The parameters for the slower UFO do not differ significantly from those found in Parker et al. (2018b), so for that absorption we use the same derived quantities.

A lower limit on the radius of a wind comes from requiring that the wind velocity exceed the escape velocity, i.e. $v > (2GM/r)^{1/2}$. For the faster absorption, this gives a lower limit of $r > 4 \times 10^{15}$ cm (27R$_{\odot}$), compared with 1.3 $\times$ 10$^{16}$ cm (89R$_{\odot}$). An upper limit comes from requiring that the flux be high enough to ionize the gas to the observed level, given the column density (Table 2): $r < L_{\text{ion}}/E_{\text{HI}}$ (taking the ionizing luminosity of $\sim 1 \times 10^{45}$–$1 \times 10^{46}$ erg s$^{-1}$ from the X-ray and EUV fluxes from SED modelling in Lee et al.)
2013). This gives a range of $1.5 \times 10^{17} \text{--} 1.5 \times 10^{18}$ cm (1000--10 000$R_{G}$) for the slower absorber, and $1.3 \times 10^{16} \text{--} 1.5 \times 10^{17}$ cm (90--900$R_{G}$) for the faster absorber.

Making the conservative assumption that the winds are located at the radii corresponding to the escape velocity and using the formula from Krongold et al. (2007), assuming the factor describing the opening and viewing angles of the wind, $f(\theta, \phi) = 1.5$, we find mass outflow rates of $2.8 \times 10^{26}$ g s$^{-1}$ and $2.6 \times 10^{25}$ g s$^{-1}$ (~4$M_{\odot}$ per year), respectively, and kinetic powers of $2.8 \times 10^{45}$ erg s$^{-1}$ and $8.5 \times 10^{45}$ erg s$^{-1}$ (0.02 and 0.07 $L_{\text{Edd}}$). These values are approximate, but they are consistent with a wind model where multiple streamlines cross the line of sight, with faster, hotter material located at smaller radii (e.g. Fukumura et al. 2015), and meet the predicted 0.5--5% threshold for AGN feedback (Di Matteo et al. 2005; Hopkins & Elvis 2010).

An alternative model for strongly blueshifted absorption lines was presented by Gallo & Fabian (2011, 2013), and recently shown to fit the spectrum of IRAS 13224-3809 by Fabian et al. (2020). In this scenario, the blueshifted absorption arises from a surface layer on the disk where these relativistic velocities arise naturally. While this is not the focus of this letter, we note that this model could produce an apparently weaker Fe Ka line as only the reflected emission is affected by the absorption, so an increase in the powerlaw continuum would reduce the apparent equivalent width of the stronger Ka line more than Kβ.

4.3 Comparison with PDS 456

Unlike the faster UFO zone identified in PDS 456 (Reeves et al. 2018), this feature appears to be persistent. Assuming that the possible feature identified at the same energy in Parker et al. (2018b) is the same as the feature we find with the new observations, then it has persisted for over a decade without significant changes. The most likely explanation for this is that the XMM–Newton and NuSTAR observations of IRAS 13349+2438 have all occurred at roughly the same flux level, despite the high variability of the source on long timescales (Parker et al. 2018b). The strength of the UFO lines in PDS 456 appears to be flux dependent (Parker et al. 2018a), as in other sources (Parker et al. 2017b,a; Pinto et al. 2018; Igo et al. 2020), and the range of fluxes observed in PDS 456 is much greater than in IRAS 13349+2438 (e.g. Matzeu et al. 2017). It therefore seems likely that the equivalent material in PDS 456 is fully ionized for a large fraction of the time. Further observations of IRAS 13349+2438 aimed at high or low flux states should be able to determine whether the same behaviour takes place in this source.

5 CONCLUSIONS

We have presented new X-ray observations of the quasar IRAS 13349+2438 with NuSTAR and XMM–Newton. The spectra show a firm detection of a second Fe absorption line, likely from a second layer of gas with a velocity of $v \approx 0.27c$. This is consistent with a stratified wind scenario, where faster streamlines, higher ionization streamlines originate from the inner accretion disk, and slower, colder streamlines are launched further out.

We also find multiple Lyα lines at low energies in a stacked XMM–Newton EPIC-pn spectrum including all archival data. These lines are consistent with the blueshift of the lower velocity Fe line, suggesting a common origin.

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DATA AVAILABILITY

The data underlying this article are subject to an embargo of 12 months from the date of the observations. Once the embargo expires the data will be available from the XMM-Newton science archive (http://nxsa.esac.esa.int/) and the NuSTAR archive (https://heasarc.gsfc.nasa.gov/docs/nustar/nustar_archive.html).

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