Tracking X-ray Outflows with Optical/IR Footprint Lines

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ABSTRACT

We use Cloudy photoionisation models to predict the flux profiles for optical/IR emission lines that trace the footprint of X-ray gas, such as [Fe X] 6375Å and [Si X] 1.43μm. These are a subset of coronal lines, from ions with ionisation potential ≥ that of O VII, i.e., 138eV. The footprint lines are formed in gas over the same range in ionisation state as the H and He-like of O and Ne ions, which are also the source of X-ray emission lines. The footprint lines can be detected with optical and IR telescopes, such as the Hubble Space Telescope/STIS and James Webb Space Telescope/NIRSpec, and can potentially be used to measure the kinematics of the extended X-ray emission gas. As a test case, we use the footprints to quantify the properties of the X-ray outflow in the Seyfert 1 galaxy NGC 4151. To confirm the accuracy of our method, we compare our model predictions to the measured flux from archival STIS spectra and previous ground-based studies, and the results are in good agreement. We also use our X-ray footprint method to predict the mass profile for the X-ray emission-line gas in NGC 4151 and derive a total spatially-integrated X-ray mass of 7.8(±2.1) × 10^5 M\(_{\odot}\), in comparison to 5.4(±1.1) × 10^5 M\(_{\odot}\) measured from a Chandra X-ray analysis. Our results indicate that high-ionisation footprint emission lines in the optical and near-infrared can be used to accurately trace the kinematics and physical conditions of AGN ionised, X-ray emission line gas.

Key words: galaxies: active – Seyferts: emission lines – galaxies: kinematics and dynamics – X-rays: galaxies

1 INTRODUCTION

1.1 General Background

Active Galactic Nuclei (AGN) are powered by accretion of matter onto Supermassive Black Holes (SMBHs), with masses ≥ 10^6 M\(_{\odot}\). This process of feeding the SMBH creates large amounts of electromagnetic radiation from the accretion disk of the black hole, which can accelerate winds, and may produce feedback (e.g., Begelman 2004). These winds, if producing efficient feedback, evacuate the bulge of the host galaxy, quenching star formation, which is believed to produce the well-known relationship between the mass of the SMBH and the mass of the bulge (e.g., Gebhardt et al. 2000).

In order to investigate how effective AGN feedback is on galactic-bulge scales, as required in a star-formation quenching, negative feedback scenario, it is important to quantify the mass outflows properties and their impact on the host galaxy. The physical properties of the gas, such as mass, mass outflow rates and kinetic energy can be estimated by photoionisation models (e.g., Crenshaw & Kraemer 2007). These models, combined with emission-line studies, particularly those utilising high spatial-resolution (e.g., Fischer et al. 2017; Trindade Falcão et al. 2021a; Revalski et al. 2021), provide the most accurate method to calculate critical quantities of these winds, such as the masses, velocities, outflow rates, and kinetic energies, as a function of distance from the SMBH. The strength of the AGN-driven winds can be quantified in the form of kinetic luminosity, \( \dot{E}(r) = \frac{1}{2} M_{\text{out}} v^2 \), where the mass outflow \( M_{\text{out}}(r) = 4\pi r N_H \mu m_p C_g v_r \), and \( r \) is the radial distance from the SMBH, \( N_H \) is the column density, \( \mu \) is the mean mass per proton, in this case \( \mu = 1.4 \), \( m_p \) is the proton mass, \( C_g \) is the global covering factor of the gas, and \( v_r \) is the radial velocity. Studies for efficient feedback require \( \dot{E}(r) \sim 0.5\% - 5\% \) of \( L_{\text{bol}} \), the bolometric luminosity of the AGN radiating at near their Eddington limit (Di Matteo et al. 2005; Hopkins & Elvis 2010). In addition, the amount of kinetic energy deposited into the host galaxy rises rapidly with the velocity of the gas, since \( \dot{E} \propto v^3 \).

Our studies of mass outflow in nearby AGN show that, even though these outflows are very massive and inject considerable amounts of kinetic energy in the bulge of the host galaxy, they do not extend far enough to clear the bulge of gas (Fischer et al. 2018) and also lack the power to do so (Trindade Falcão et al. 2021a), since their \( \dot{E}(r)/L_{\text{bol}} \) ratio does not reach the required 0.5% for efficient feedback. Therefore, these results suggest that winds of optical emission-line gas are not an efficient form of AGN feedback (e.g., Trindade Falcão et al. 2021a). However, these results do not take into account the role of higher-ionisation gas in this process of AGN feedback, which means...
that it is possible that X-ray winds are responsible for the dynamic effects we observe in nearby AGN (Trindade Falcão et al. 2021b).

Extended soft X-ray emission, co-located with the [O III] emission-line gas, was detected by Chandra/Advanced CCD Imaging Spectrometer (ACIS) in nearby Seyfert galaxies (Ogle et al. 2000; Young et al. 2001). In addition, Chandra imaging has been used to map the Narrow Line Region (NLR) X-ray emission in several Seyferts (e.g., Bianchi et al. 2010; Gonzalez-Martín et al. 2010; Wang et al. 2011b,a,c; Maksym et al. 2019). By isolating bands dominated by specific emission-lines, these authors were able to derive constraints on the structure of the X-ray emission-line regions. Notably, Wang et al. (2011b) and Maksym et al. (2019) suggest that there is evidence for shocks, which indicates interaction of the X-ray with the ISM of the host galaxy.

Even though it is possible to obtain data with good spectral resolution with Chandra/HETG (e.g., Kallman et al. 2014; Kraemer et al. 2020), as well as kinematics and detailed physical insights, it is challenging to obtain detailed spatially-resolved information from these data. For instance, in their study of NGC 4151, Kraemer et al. (2020) were not able to get any accurate kinematic profiles from the HETG data, even for such a nearby AGN. Therefore, we have no means to determine what role this high ionisation gas plays in the process of AGN feedback.

Alternatively, a model for X-ray gas, characterised by a log $U$ = 0.0 predicts strong optical and IR emission lines (see Section 2), which can be considered as “footprints” of the X-ray wind (e.g., Porquet et al. 1999). Since these footprint lines could be detected using ground-based near-infrared telescopes (e.g., Rodríguez-Ardila et al. 2011; Lamperti et al. 2017) or the James Webb Space Telescope (Satyapal et al. 2021) and HST/STIS, it provides an opportunity to accurately constrain the kinematics of the X-ray wind.

### 1.2 Evidence for X-ray feedback

In our most recent paper (Trindade Falcão et al. 2021b), we analysed the dynamics of mass outflows in the NLR of the QSO2 Mrk 34. We presented evidence for the presence of X-ray winds in the NLR of this QSO2 by performing an analysis based on the kinetic energy density of the [O III]-emitting gas and the X-ray winds, and also by suggesting that high velocity gas is being accelerated in-situ via entrainment by X-ray winds (for details see Trindade Falcão et al. 2021b).

We also used Cloudy photoionisation models (Ferland et al. 2017) to calculate the integrated fluxes for some of the X-rays footprints,

$$ U = \frac{Q}{4 \pi n_H r c} $$

where, $n_H$ is the hydrogen number density, $r$ is the distance to the ionising source, $c$ is the speed of light, and the ionising luminosity, $Q = \int L_\nu \, d\nu$, where $h \nu_0 = 13.6$eV.
i.e., [Si X] 1.43 μm and [Fe X] 6375Å. Even though our X-ray models provided predictions for the [Fe X] that were consistent with the optical spectra, our parameterisation of the physical properties of the X-ray winds were determined indirectly, by its inferred dynamical effects and the distributions of the [O III] gas in the NLR of Mrk 34. Therefore, although we were able to obtain results that were consistent with the X-ray emission detected in the Chandra/ACIS image, this does not present itself as a well-constrained model of the X-ray wind.

Kraemer et al. (2020) analysed Chandra/HETG spectra of the X-ray emission-line gas in NGC 4151. The zero-th order data show extended H- and He-like O and Ne, up to a distance r ~ 200 pc from the nucleus. They determined that the total mass of the ionised gas is \( \sim 5.4 (\pm 1.1) \times 10^5 \) M\(_{\odot}\). In addition, by assuming the same kinematic profile as that for the [O III] gas, derived from the analysis by Kraemer et al. (2000) of HST/STIS spectra, the peak X-ray mass outflow rate was \( \approx 1.8 \) M\(_{\odot}\) yr\(^{-1}\), at r ~ 150 pc. The total mass and mass outflow rates are similar to those determined using [O III] (Crenshaw et al. 2015), which implies that the X-ray gas is a major outflow component. In addition, the fact that it does not appear to be a drop in mass outflow rates for distances greater than 100 pc may indicate that the X-ray component has a greater effect on the host galaxy than the optical/UV gas and that X-ray winds might be a more efficient mechanism for AGN feedback.

Nevertheless, even though the use of Chandra/HETG to characterise the X-ray outflows in NGC 4151 is an improvement compared to the ACIS imaging data used in Trindade Falcão et al. 2021b to analyse the X-ray winds in Mrk 34, this analysis can only be used to obtain spatially-resolved spectra for the most nearby AGN. Additionally, the use of Chandra/HETG is still not enough to fully characterise the extended emission, since this method does not provide accurate spatially resolved kinematics. For this reason Kraemer et al. (2020) made the assumption that the X-ray gas follows the [O III] kinematics and used the [O III] kinematic profile to track the X-ray gas in NGC 4151. In the present study we address this problem by analysing the X-ray outflows in NGC 4151 using a different methodology.

In this paper, we model the X-ray footprint lines using Cloudy photoionisation models, which allows us to construct radial flux profiles for these lines. We then compare our predictions to the results of Kraemer et al. (2020) for NGC 4151. In section 3 we present our photoionisation modeling analysis. In section 4 we present a comparison between our modeling results and the results of Kraemer et al. (2020). Finally, in sections 5 and 6 we discuss our results and present our conclusions, respectively.

2 THE STUDY OF OPTICAL/IR X-RAY FOOTPRINT LINES

In order to explore the relation between the footprint lines and the X-ray lines we generate a grid of Cloudy models using Mrk 34’s SED and abundances, as discussed in Trindade Falcão et al. 2021a. Our models consider a range in \( N_H \) of \( 10^{20.5} \) - \( 10^{23.3} \), a range in \( \log U \) of (-1.50) - (1.00), and constant density, as the fractional abundance is not a strong function of density. Figure 1 shows the Cloudy model predictions for the relative abundance of the Fe, Si, and Ca ions, compared to H and He-like O and Ne, as a function of the ionisation parameter and column density. The fact that these lines are formed in gas over the same range in ionisation state indicates that they will be formed in gas that will also be the source of X-ray emission-lines, detected in the HETG or XMM-Newton/Reflection Grating Spectrometer spectra.

It is important to distinguish between coronal lines and footprint lines. Coronal lines are emission-lines formed from very highly ionised atoms, and they possess this name because they were first observed in the solar corona (e.g., Mazzalay et al. 2010). These lines are collisionally excited forbidden transitions within low-lying levels of highly ionised species with ionisation potentials (IP) ≥ 100 eV. They have been detected in the optical and IR spectra of all types of Seyfert galaxies (e.g., Seyfert 1943; Nagao et al. 2000; Rodríguez-Ardila et al. 2002; Landt et al. 2015), and represent one of the key gaseous components of the active nucleus. They appear to be approximately equally abundant in type 1 and type 2 AGN (e.g., Rodríguez-Ardila et al. 2011).

On the other hand, we define footprint lines to be a subset of “coronal” lines from ions with IP ≥ 138 eV, i.e., that of O VII, which peak over the same range in ionisation parameter as the H and He-like ions (see Figure 2). For instance, as shown in Figure 1 (top right panel), the fractional abundance for Fe VII, a ionisation state which produces a coronal line, peaks at low \( U \approx -1.0 \). Even though its peak ionisation parameter is fairly close to that of O VII, the peak flux of the OVII 22.1Å line is at significantly higher \( U \). Additionally, the peak ionisation of O VIII, Ne IX, and Ne X are all at low \( U > 0 \). On the other hand, the fractional abundance for Fe X, a ionisation state which produces a photoionization line, peaks at low \( U \approx 0.0 \), i.e., at the same ionisation parameter as the X-ray ions. It is also important to note here that the peak ionization abundance corresponds to the peak flux for collisionally excited lines, like the footprint lines, but not the X-ray lines. These are primarily due to recombination in photo-ionised plasma, as shown in Figure 1, hence peak at somewhat higher \( U \) than where the ionizing ionisations are greatest.

In addition, due to its high ionisation the gas is optically thin to the ionising radiation over a large range in column density, which means that our results are not a strong function of the column density of the gas. For example, in Figure 1 we present the results for the Cloudy model predictions for the fractional abundances of relevant ionisation states of iron and silicon and H- and He-like oxygen and neon, for the following column densities: \( N_H \approx 10^{21.5} \) cm\(^{-2}\) (top left panel), \( N_H \approx 10^{20.5} \) cm\(^{-2}\) (top right panel), \( N_H \approx 10^{22.5} \) cm\(^{-2}\) (bottom left panel), and \( N_H \approx 10^{21.5} \) cm\(^{-2}\) (bottom right panel). As we can see, the ions from which the footprint lines originate and H- and He-like ions still coexist over the same range in ionisation parameter in a gas with different column densities, which means that our results do not change over a factor of \( > 1000 \) in \( N_H \).

Furthermore, we also analyse the effect of different SEDs on the fractional abundances of the relevant ionisation states shown in Figure 1. We use five different SEDs to perform this analysis, specifically, the SED presented by Romano et al. (2004) for the Narrow-Line Seyfert 1 Galaxy Arakelian 564, and the SEDs discussed by Melén-
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dez et al. (2011). Since the choice of SED does not have a significant effect on the accuracy of our method, and to avoid interrupting the flow of the paper, we present these results in Appendix A.

An important point that should be addressed here is the location of [Si VII] and [Mg VII] in Figure 2. One could think that, since the ionisation parameter where their ionic abundances peak is \(< \log U = 0.5\), these lines are not footprint lines, even though they satisfy our requirement for their IP, i.e., \( \log P \geq 138 \text{eV} \). However, this phenomenon may be due to dielectronic recombination rates (e.g., Kraemer et al. 2004; Netzer 2004). Specifically, if these rates are too low, the \( \log U \) values where the ionic abundances peak will also be too low. For example, a shift of 0.25 to 0.5 dex would be enough to place [Si VII] and [Mg VII] into the "footprint" range.

3 PHOTOIONISATION MODELING ANALYSIS

3.1 Photoionisation Models

For our analysis, we generate photoionisation model grids, computed using Cloudy (version 17.00; Ferland et al. 2017). We assume a continuum source with a SED that can be fitted using a power law of the form \( L_\nu \propto \nu^{-\alpha} \). For our study we adopt the same SED used by Kraemer et al. (2020) in their study on NGC 4151, i.e.

\[
\begin{align*}
\alpha &= 1.0 \text{ for } 1 \times 10^{-4} \leq \nu \leq 13.6 \text{ eV}; \\
\alpha &= 1.3 \text{ for } 13.6 \text{ eV} \leq \nu \leq 500 \text{ eV}; \\
\alpha &= 0.5 \text{ for } 500 \text{ eV} \leq \nu \leq 30 \text{ keV}; \\
\end{align*}
\]

In addition, the choice of input parameters, specifically, the radial distances of the emission-line gas with respect to the central source \( \alpha \) of the assumed SED and a distance of 15 Mpc. They obtained a value \( \alpha \) of the assumed SED and a distance of 15 Mpc. They obtained a value of \( Q = 3 \times 10^{53} \text{ photons s}^{-1} \) and a bolometric luminosity \( L_{bol} = 1.4 \times 10^{44} \text{ erg s}^{-1} \) or 0.03 of the Eddington Luminosity.

In addition, the elemental abundances in the NLR of NGC 4151 were initially determined in Kraemer et al. 2000, and based on recent estimates of solar elemental abundances (e.g., Asplund et al. 2005), they correspond to roughly 1.4x solar. We assume the same values for the present paper, as follows (in logarithm, relative to H, by number):

\[
\begin{align*}
\text{He}^+ &= -1.00, \text{ C}^4 &= -3.47, \text{ N}^+ &= -3.92, \text{ O}^+ &= -3.17, \text{ Ne}^+ &= -3.96, \text{ Na}^+ &= -5.76, \\
\text{Mg}^+ &= -4.48, \text{ Al}^+ &= -5.55, \text{ Si}^+ &= -4.51, \text{ P}^+ &= -6.59, \text{ S}^+ &= -4.82, \text{ Ar}^+ &= -5.60, \\
\text{Ca}^2+ &= -5.66, \text{ Fe}^2+ &= -4.4, \text{ and Ni}^2+ &= -5.78.
\end{align*}
\]

We also generate photoionisation models that account for internal dust, assuming grain abundances of 50% of those determined for the interstellar medium (ISM) (e.g., Mathis et al. 1977), with the depletions from gas phase scaled accordingly (e.g., Snow & Witt 1996), i.e., \( \text{C}^4 = -3.64, \text{ O}^+ = -3.29, \text{ Mg}^+ = -4.78, \text{ Al}^+ = -6.45, \text{ Si}^+ = -4.81, \text{ Ca}^2+ = -5.96, \text{ Fe}^2+ = -4.70, \) and \( \text{Ni}^2+ = -6.08 \). These depletions are consistent with more recent studies (e.g., Mehdipour & Costantini 2018). The grain abundances of 50% is the same as that adopted by Kraemer et al. (2000) in their photoionisation study of the NLR of NGC 4151.

If the X-ray gas was created from the expansion of [O III] clouds, as discussed in Trindade Falcão et al. 2021b, we expect it to possess internal dust, since the predicted dust temperatures of the X-ray models are too low to be able to destroy the dust grains (e.g., Barvainis 1987). On the other hand, the destruction of dust grains is possible as a result of shocks. If the X-ray gas is entraining clouds of [O III]-emitting gas (Trindade Falcão et al. 2021b) and effectively “sweeping” them up, the shocks that occur during this process could be enough to shatter the dust grains within the gas (e.g., Jones et al. 1997). Our assumption of lower than ISM grain abundance is consistent with this scenario.

3.2 Radial Flux Distributions

In their study, Kraemer et al. (2020) calculated the emitting area for the X-ray emitting gas. They were able to do this calculation only for Ne IX 13.69Å and Ne X 12.13Å, since the loss of soft-Xray sensitivity for ACIS made it hard to accurately measure the O VII 22.1Å and O VIII 18.97Å fluxes. To construct the radial flux profiles associated with each emission-line, we redo their analysis, and include in our study other X-ray line profiles, e.g., O VII 22.1Å and O VIII 18.97Å. In addition, in our study, we only generate photoionisation models for the medium ionisation component from Kraemer et al. 2020. The reason is that the highest ionisation models did not predict significant fluxes for the footprint lines. The complete set of parameters used to generate our models is listed in Table 1.

Using the Cloudy predictions for the X-ray footprint lines, and the emitting areas calculated in Kraemer et al. 2020, we also construct radial flux profiles for the footprint lines, such as [Fe X] 6375Å and [Si X] 1.43µm. Our results are shown in Figure 3 and 3 (Cont.), for the optical/IR lines, and in Figure 4 for the X-ray lines. It is important to note that our radial flux profiles show two different sets of models: dust-free and 50% dust. The major effect for the dusty models is the depletion of elements onto dust grains. For example, since sulfur and neon are not depleted from gas phase, the [S X], Ne IX and Ne X do not show any significant differences, other than a slight increase at the points closest to the AGN. The resulting spatially-integrated fluxes for all the footprint and X-ray lines are listed in Table 2.

It is important to note that a few of our predicted flux profiles, such as [Ca VIII], and [Fe VII] (see Figure 3) show a higher predicted flux for the dusty models in the center bins. This is because the He II zone is shallower when dust is present, which results in greater recombination into those ionisation states. However, the effect is not present for the more distant points, because \( N_H \) is smaller (see Table

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Table 1. Cloudy Model Parameters. The models follow the same parameters as the medium ionisation component from Kraemer et al. 2020.

| Distance\( ^a \) | \( \log U \) | \( \log n_H^c \text{ cm}^{-3} \) | \( \log N_H^b \text{ cm}^{-2} \) |
|-----------------|---------|-----------------|-----------------|
| 12 pc           | 0.05    | 2.71            | 22.28           |
| 50 pc           | -0.17   | 1.69            | 21.88           |
| 100 pc          | -0.27   | 1.19            | 21.38           |
| 153 pc          | -0.34   | 0.89            | 21.06           |
| 205 pc          | -0.38   | 0.68            | 20.81           |
| 257 pc          | -0.42   | 0.52            | 20.71           |
| 309 pc          | -0.45   | 0.39            | 20.58           |
| 360 pc          | -0.47   | 0.28            | 20.27           |
| 412 pc          | -0.49   | 0.18            | 20.37           |
| 464 pc          | -0.50   | 0.09            | 20.28           |

\( ^a \) Assuming \( \delta r/r < 1 \) or \( \delta r \) fixed at 50 pc, where \( \delta r \) is the deprojected width for each extraction bin; for a detailed explanation, see Kraemer et al. 2020.

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\footnote{The model predictions for the ions fractional abundances present in Figure 1 use the SED of Mrk 34 (Trindade Falcão et al. 2021a) and parameters as discussed in the caption of the figure.}
Figure 3. Computed radial flux distributions for X-ray footprint lines [Al IX] 2.04μm, [Ca VIII] 2.32μm, [Fe VII] 6078Å, [Fe X] 6375Å, [Fe XI] 7892Å, [Fe XIV] 5303Å, [Mg VII] 5.50μm, and [Mg VIII] 3.02μm. The fluxes are obtained using the analysis described in section 3. The dust-free models are plotted in red and the 0.5 ISM models are plotted in blue. The models assume δr/r < 1 or δr fixed at 50pc, where δr is the deprojected width for each extraction bin. The uncertainties were obtained based on the S/N of the fluxes in the 0th order image from Kraemer et al. 2020. The positive and negative distances correspond to point SW and NE of the nucleus, respectively.

1), hence the model integrations do not reach the end of the He II zone (see discussion in Kraemer & Harrington 1986).

4 FOOTPRINTS OF X-RAY OUTFLOWS

4.1 Observational Limits on the Footprint Lines

By analysing the archival STIS long-slit spectra, we are able to obtain the spatial [Fe X] and [O III] distribution in NGC 4151, as shown in Figure 5. Specifically, since the [Fe X] 6375 emission-line is contaminated by [O I] 6364, we obtain an intrinsic [Fe X] brightness profile by subtracting 1/3 of the [O I] 6300 flux at each point along the slit. In addition, in order to account for the mass of [Fe X] emitting gas outside of the area sampled by the STIS slit, we use an archival HST/WFPC2 [O III] image of the NLR for the target (Kraemer et al. 2020). We measure the [O III] fluxes in regions of 0''.5x3''0, centered at the nucleus, along a position angle of 140°.

We then measure the ratio [Fe X]/[O III] inside the STIS slit, which allow us to obtain the full [Fe X] flux distribution. In Figure 6, we compare the results of our predicted [Fe X] flux profiles (both
Figure 3 (Cont.). Computed radial flux distributions for X-ray footprint lines [S IX] 1.25\(\mu\)m, [Si VII] 2.48\(\mu\)m, [Si IX] 3.92\(\mu\)m, and [Si X] 1.43\(\mu\)m.

Figure 4. Computed radial flux distributions for X-ray lines O VII 22.1Å, O VIII 18.97Å, Ne IX 13.69Å, and Ne X 12.13Å. The fluxes are obtained using the analysis described in section 3. The dust-free models are plotted in red and the 0.5 ISM models are plotted in blue. The models assume \(\delta r/\tilde{r} \leq 1\) or \(\delta r\) fixed at 50pc, where \(\delta r\) is the deprojected width for each extraction bin. The uncertainties were obtained based on the S/N of the fluxes in the 0th order image from Kraemer et al. 2020.

for dust-free models and 50% dust models) and the results of the full [Fe X] flux distribution (inside and outside the slit). The total spatially-integrated [Fe X] flux, i.e., the sum of the fluxes inside and outside the STIS slit, is \(1.9^{+0.2}_{-0.1} \times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\). It is important to note here that the flux profiles show lower fluxes for the negative distances. This is because the observed fluxes are asymmetric around the nucleus, which is not easily seen in Figure 5, since the slit did not cover the entire NLR.

In addition, based on the analysis of the STIS long-slit spectra, we are able to calculate an upper limit, integrated over 11 pixels (0.1" \times 0.55"), for the flux of the [Fe XIV] 5303Å line < 7.5 \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), which agrees with our predicted flux of 1.3 \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) (see Table 2). Considering that the brightness profile for [Fe XIV] follows the same brightness profile as [Fe X], we calculate an upper limit in the central bin 0.1" \times 0.05" < 2.6 \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), which also agrees with our predicted value of
1.0 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}. It is important to note here that the other optical footprint lines are below the detection limit of STIS.

### 4.2 Predicting the Mass of the Extended Gas

In order to recompute the mass of the extended X-ray gas in NGC 4151 based on our X-ray footprint analysis, we use our predicted [Fe X] radial flux profile. It is important to note here that the methodology used in this study to estimate the mass of the extended X-ray gas in the target is different from the methodology used by Kraemer et al. (2020). Kraemer et al. (2020) mapped the Ne IX triplet (the resonance line, 13.50Å, the intercombination line, 13.60Å, and the forbidden line, 13.73Å) and Ne X α, instead of [Fe X], and applied the model parameters to fit the 0th order emission-line profiles of these lines.

We calculate the masses in each bin by using the line luminosities and the Cloudy-predicted fluxes for the [Fe X], as follows:

\[
M_{\text{bin}} = N_H \mu \frac{L_{[\text{Fe} \ X]} c}{F_{[\text{Fe} \ X]}}
\]  

where \(N_H\) is the hydrogen column density of each photoionisation model generated by Kraemer et al. (2020), assumed to be the same as the column density modelled by Cloudy, \(\mu\) is the mean mass per proton, which we assume to be 1.4 (consistent with roughly solar abundances), and \(m_p\) is the mass of a proton. In order to get the mass of [Fe X] the column density needs to be multiplied by an effective area. The term in parentheses gives the effective surface area of the emitting gas as seen by the observer. \(F_{[\text{Fe} \ X]}\) is the [Fe X] luminosity per cm², predicted by Cloudy, and \(L_{[\text{Fe} \ X]}\) is the observed luminosity determined using the total flux. Specifically,

\[
L_{[\text{Fe} \ X]} = 4\pi D^2 F_{[\text{Fe} \ X],\text{total}}
\]

where \(D\) is the distance to NGC 4151, and \(F_{[\text{Fe} \ X],\text{total}}\) is the total [Fe X] flux. Physically, the equation for \(M_{\text{slit}}\) determines the area of the emitting clouds through the ratio of the luminosity and flux, and then multiplies this by the column density to yield the total number of particles, which, when multiplied by the mean mass per particle, gives the total ionised mass. The total mass of X-ray-emitting gas is \(7.8 \pm 2.1) \times 10^{50} M_\odot\) with the uncertainties being added in quadrature for each bin, and the mass profile for the target is shown in Figure 7 (purple points). We compare our results to the results of Kraemer et al. 2020, as shown in Figure 7 (orange points), which found that the total mass of X-ray gas within the outflow regions for NGC 4151 is \(5.4(\pm1.1) \times 10^{50} M_\odot\).

Even though our results for the total mass of X-ray-emitting gas are very promising, due to the poor resolution of the STIS grating used for this observation, along with a low S/N, we are not able to obtain any accurate kinematic information for [Fe X]. This means that we cannot compute the outflow rates for NGC 4151, and a comparison to the values for \(M\) found by Kraemer et al. (2020), i.e., \(M = 1.8 M_\odot \text{ yr}^{-1}\), is not possible given the available STIS low-dispersion spectrum.

### 5 DISCUSSION

In Figure 8 we present the Cloudy-predicted [Fe X]/Hβ (in red), O VII (22.1Å)/Hβ (in blue), and O VII (21.6Å)/Hβ (in green) ratios for NGC 4151, for the 50% dust fraction models. It is possible to see that when densities are very high, i.e., \(\geq 10^9 \text{ cm}^{-3}\), the [Fe X]/Hβ ratio starts to drop, which means that the [Fe X] 6375Å line starts to become collisionally suppressed. However the O VII (22.1Å)/Hβ ratio also drops with increasing density, hence [Fe X] still tracks the O VII 22.1Å emission. On the other hand, the O VII 21.6Å line is not suppressed over this range in density. Therefore, there could be a contribution to the X-ray emitting gas from denser regions, close to the AGN. However, for NGC 4151, Q \(\approx 3 \times 10^{53}\) photons \text{s}^{-1} (e.g., Kraemer et al. 2020), so gas characterised by logU = 0.0 with densities of \(\approx 10^9 \text{ cm}^{-3}\) would lie at \(r \approx 2.8 \times 10^6\) cm from the central SMBH, which is just at the outer edge of the BLR (about 10 light-days) (e.g., Bentz et al. 2013). The fact that our predicted values for the mass of X-ray-emitting gas in NGC 4151 agree very well with the measured values by Kraemer et al. (2020) (see Figure 7) tells us that the contribution from X-ray gas that is located in the BLR of this AGN is negligible. This result is consistent with the findings of Crenshaw & Kraemer (2007), which shows that the mass outflows from the dense inner region of the AGN do not contribute
the percentage of dust within the gas, as shown in Figure 3 (Cont.), tells us that this line might be a good choice of footprint line when the percentage of dust within the gas is unknown (but see below). On the other hand, for lines like [Fe X] 6375Å, and [Mg VIII] 3.02μm it is important to have a good estimate of the amount of dust present in the gas, since their fluxes are strongly affected by depletion of these element onto dust grains. For instance, if one uses only the [Fe X] 6375Å line to predict the emission of X-ray gas, but underestimates the amount of dust within the gas, the estimated X-ray mass could be overestimated, since the dusty models predict lower fluxes, as shown in Figure 3.

In addition, Rodríguez-Ardila et al. (2011) measured the fluxes of IR footprint lines for NGC 4151 in their study of near-infrared coronal line spectrum of nearby AGN. As shown in Table 2, our predicted fluxes for [Al IX] 2.04μm and [Si IX] 1.43μm agree well with the results of Rodríguez-Ardila et al. (2011). The under-prediction of [Ca VIII] 2.32μm is consistent with the fact that Ca VIII peaks at much lower ionisation than our X-ray models (see Figure 1). Regarding the discrepancy between our measured flux for the [S IX] 1.25μm and the observed flux from Rodríguez-Ardila et al. 2011, we believe that our underpredicted value could be due to collision strength of this transition (e.g., Zhang & Sampson 2002), or due to an unmodeled process, such as photo-excitation/fluorescence.

It is important to note that, in this study, we use [Fe X] as a tracer for X-ray outflows based on the characteristics of NGC 4151, i.e., the fact that this target is not a very powerful AGN. For AGN with more highly ionised gas in their NLR, other lines would be a better choice, such as [Si X] and [Fe XIV], as shown in Figure 1. For instance, based on our predicted flux and observed flux for [Fe XIV] 5303Å, there is not a large amount of [Fe XIV] in NGC 4151 and this is because there is only a small amount of high ionisation gas in the NLR of this target. For more powerful targets, e.g., quasars, the use of [Fe XIV] as a tracer might be preferable, since these objects are more luminous and powerful than NGC 4151.

Table 2. Predicted Spatially-Integrated Fluxes. In boldface are the emission-lines that we define as footprint lines, i.e., lines from ions with IP ≥ 138 eV.

| Ion   | Wavelength | IP (eV) | Peak log\(U^*\) | Predicted Flux d\(a\) (10\(^{-16}\) erg s\(^{-1}\) cm\(^{-2}\)) | Predicted Flux d\(b\) (10\(^{-16}\) erg s\(^{-1}\) cm\(^{-2}\)) | Observed Flux (10\(^{-16}\) erg s\(^{-1}\) cm\(^{-2}\)) |
|-------|------------|---------|------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| [Al IX] | 2.04μm    | 284     | 0.0              | 51.8 (±4.8)                                     | 6.9 (±0.6)                                       | 23 (±16)                                       |
| [Ca VIII] | 2.32μm   | 127     | -0.75            | 3.9 (±0.6)                                      | 5.3 (±0.5)                                       | 515 (±23)                                      |
| [Fe VII] | 6087Å     | 99      | -1.0             | 15.4 (±2.0)                                     | 26.5 (±2.5)                                     | -                                             |
| [Fe X] | 6375Å      | 234     | 0.0              | 2360 (±215.0)                                    | 1050 (±96.2)                                    | 1900 (±75)                                    |
| [Fe XI] | 7892Å      | 262     | 0.25             | 921 (±87.7)                                     | 302 (±27.7)                                     | -                                             |
| [Fe XIV] | 5303Å     | 361     | 0.5              | 130 (±15.6)                                     | 34.0 (±3.4)                                     | -                                             |
| [Mg VII] | 5.50μm    | 186     | -0.75            | 35.2 (±4.2)                                     | 37.1 (±3.4)                                     | -                                             |
| [Mg VIII] | 3.02μm    | 225     | -0.25            | 251 (±24.8)                                     | 174 (±15.9)                                     | -                                             |
| [S IX] | 1.25μm     | 328     | -0.25            | 22.0 (±2.2)                                     | 31.1 (±2.9)                                     | 397 (±23)                                     |
| [Si VII] | 2.48μm    | 205     | -1.0             | 14.6 (±1.7)                                     | 16.9 (±1.5)                                     | -                                             |
| [Si IX] | 3.55μm    | 303     | 0.0              | 319 (±33.0)                                     | 195 (±17.3)                                     | -                                             |
| [Si X] | 1.43μm     | 351     | 0.25             | 559 (±51.9)                                     | 214 (±19.5)                                     | 377 (±30)                                     |
| O VII $\alpha$ | 22.1Å   | 138     | -0.5             | 3940 (±359.0)                                    | 3230 (±293.0)                                   | 3400 (±769)                                    |
| O VIII $\alpha$ | 18.97Å  | 739     | 0.25             | 610 (±146.0)                                    | 880 (±79.5)                                     | 1089 (±192)                                    |
| Ne IX $\alpha$ | 13.69Å  | 239     | 0.0              | 851 (±79.4)                                     | 747 (±69.1)                                     | 1041 (±96)                                    |
| Ne X $\alpha$ | 12.13Å  | 1195    | 0.0              | 204 (±19.8)                                     | 166 (±15.8)                                     | 480 (±48)                                     |

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Figure 7. A comparison between the results of our predicted masses for the X-ray-emitting gas (purple points) and the results of Kraemer et al. 2020 (orange points). The uncertainties were obtained based on the S/N of the fluxes in the 0th order image from Kraemer et al. 2020.

Figure 8. Correlation between the mass of X-ray-emitting gas in NGC 4151 and the X-ray flux from Kraemer et al. 2020.
6 CONCLUSIONS

Based on our analysis derived from Cloudy photoionisation models, we present a new method that can be used to model X-ray outflows. Our conclusions are as follows:

1. There are ions that peak over the same range in ionisation parameter as the H and He-like ions and can produce detectable optical/IR emission lines, which we call "footprint lines". These lines can be detected and spatially-resolved, e.g., via HST or JWST observations and, therefore, can be used to accurately measure the kinematics and the dynamics of the extended X-ray gas. For instance, footprint lines such as [Al IX], [Si VII], [Si IX], and [Si X] can be observed with JWST, and, for NIRSpec IFU, where most of the footprint lines are, the spectral resolving power R~100, 500, 1000s (depending on the mode) corresponds to a velocity resolution of <100-300 km/s, which will allow us to obtain good kinematic information on the targets and, subsequently, be able to fully characterise the X-ray outflows.

2. We show that the models based on Chandra data from Kraemer et al. 2020 predict strong footprint lines, which is consistent with the HST data. We also develop flux profiles to characterise such lines.

3. By analysing the STIS long-slit spectrum and the [O III] image for NGC 4151, we are able to derive the measured flux profile for [Fe X] 6375Å within similar extraction bins.

4. We compare our model predictions to the observed flux profile for [Fe X] obtained from the analysis of the STIS G750L spectrum. Our values are in very good agreement with the measured values, which confirm the reliability of our approach. We also compare our model predictions for the IR lines to the observed fluxes from Rodríguez-Ardila et al. 2011, which confirms that our method can accurately produce mass profiles for the X-ray gas.

5. We confirm our methodology by determining the mass of X-ray gas using our models predictions and the observed flux profile for the [Fe X]. As shown in Figure 7, our values are in very good agreement with the values found by Kraemer et al. (2020), which confirms that our method can accurately produce mass profiles for the X-ray gas.

Even though we are able to produce accurate mass profiles for the X-ray gas using our method of "footprint lines", we are not able to get accurate kinematic information for these lines from the STIS data. The poor resolution of the STIS G750L grating, combined with low S/N, does not allow us to obtain the necessary kinematic information to compute the values for outflow rates of this target. It would be interesting to obtain observations with higher spectral resolution for NGC 4151, which would allow us to compute the predicted mass outflow rates and again test our proposed methodology. Another possibility is to apply this method on other AGN, such as NGC 1068, for which the combination of X-ray spectra and medium resolution STIS long-slit spectra exist. In addition, it is important to note that, even though we do not need the kinematic profiles derived from X-ray observations to apply our method, we would still need X-ray spectra to compare with photoionisation models in order to fully characterise the ionisation structure of these outflows.

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DATA AVAILABILITY

Based on observations made with the NASA/ESA Hubble Space Telescope, and available from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESAC/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

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APPENDIX A: APPENDIX A

As noted in Section 2, we also explore the effect of different SEDs on the fractional abundances of relevant ionisation states of iron and silicon and H- and He- like oxygen and neon. To perform this analysis we use the SED present by Romano et al. (2004) and the range of power-law SEDs presented by Meléndez et al. (2011). The different SEDs used and our results are shown in Figure A1.

In Figure A1 we show the results of our analysis for $\alpha = 1.0$ between $13.6 < h\nu < 1$ keV, and $\alpha = 2.5$ between $13.6 < h\nu < 1$ keV, i.e., the lower and upper values of the range modeled by Meléndez et al. (2011). As we can see in Figure A1, the ions from which the footprint lines originate and H- and He- like ions still coexist over the same range in ionisation parameter, even when considering sources with various SEDs. Note that for $\alpha = 2.5$ between $13.6 < h\nu < 1$ keV, there are relatively fewer EUV and X-ray photons, therefore the fractional abundances peak at higher ionisation parameter than for the harder SEDs, as shown at the bottom right panel in Figure A1. However, it is possible to see that the optical/IR footprint lines still coexist over the same range in ionisation parameter as the X-ray lines, which confirms the accuracy of our method, even for very soft SEDs.

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Figure A1. Top left figure: Representation of the five SEDs used in our analysis. Top right figure: Cloudy model predictions for the fractional abundances of relevant ionisation states of iron and silicon and H- and He-like oxygen and neon. The model assumptions are: abundances (1.4x solar) and spectral energy distribution (SED) from Romano et al. 2004, and constant column density $N_H = 10^{21.5} \text{ cm}^{-2}$ (e.g., Kraemer et al. 2020; Trindade Falcão et al. 2021b). As shown here, optical emission lines from ions such as Fe X, Fe XI, Fe XIV, and IR emission lines from ions such as Si X will be formed in the X-ray emitting gas and will act as X-ray “footprints” Bottom left figure: Same as top right figure, but with an SED from Meléndez et al. 2011 with $\alpha = 1.0$ between $13.6 < h\nu < 1\text{ keV}$. Bottom right figure: Same as top right figure, but with an SED from Meléndez et al. 2011 with $\alpha = 2.5$ between $13.6 < h\nu < 1\text{ keV}$. The results shown in the top-right, bottom-left, and bottom-right figures can be compared to our results using the Mrk 34 SED (Figure 1) and the results from the NGC 4151 analysis (see Table 2).