On the equivalent width of the Fe Kα line produced by a dusty absorber in active galactic nuclei

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ABSTRACT

Obscured active galactic nuclei (AGNs) provide an opportunity to study the material surrounding the central engine. Geometric and physical constraints on the absorber can be deduced from the reprocessed AGN emission. In particular, the obscuring gas may reprocess the nuclear X-ray emission producing a narrow Fe Kα line and a Compton reflection hump. In recent years, models of the X-ray reflection from an obscuring torus have been computed; however, although the reflecting gas may be dusty, the models do not yet take into account the effects of dust on the predicted spectrum. We study this problem by analysing two sets of models, with and without the presence of dust, using the one-dimensional photoionization code CLOUDY. The calculations are performed for a range of column densities ($22 < \log[N_H(cm^{-2})] < 24.5$) and hydrogen densities ($6 < \log[n_H(cm^{-3})] < 8$). The calculations show the presence of dust can enhance the Fe Kα equivalent width (EW) in the reflected spectrum by factors up to $\approx 8$ for Compton thick (CT) gas and a typical interstellar medium grain size distribution. The enhancement in EW with respect to the reflection continuum is due to the reduction in the reflected continuum intensity caused by the anisotropic scattering behaviour of dust grains. This effect will be most relevant for reflection from distant, predominately neutral gas, and is a possible explanation for AGNs which show a strong Fe Kα EW and a relatively weak reflection continuum. Our results show it is important to take into account dust while modelling the X-ray reflection spectrum, and that inferring a CT column density from an observed Fe Kα EW may not always be valid. Multidimensional models are needed to fully explore the magnitude of the effect.

Key words: galaxies: active – galaxies: Seyfert.

1 INTRODUCTION

All active galactic nuclei (AGNs) are powered by gas accreting on to a central supermassive black hole (e.g. Balbus 2003), a process which emits a significant amount of energy across the electromagnetic spectrum. Interestingly, a significant number of AGNs show the presence of local obscuration (Comastri 2004) at distances $\sim 1$–$10$ pc from the central engine (e.g. Antonucci 1993; Urry & Padovani 1995). The nature and origin of the absorbing gas is largely unknown but the gas presents an unique opportunity to study material as it transitions from the galaxy to the AGN environment.

Superimposed on to the typical $\Gamma \sim 1.8$–2 X-ray power law in AGNs (e.g. Dadina 2008; Beckmann, Soldi & Ricci 2009; Corral et al. 2011) is an Fe Kα line (e.g. Nandra & Pounds 1994; Ebisawa et al. 1996). The narrow component of the line is observed in a large number of objects (Kaspi 2001; Yaqoob et al. 2001), even in many high-redshift samples (Brusa, Gilli & Comastri 2005; Corral et al. 2008; Chaudhary et al. 2012; Iwasawa et al. 2012), and the width of the line indicates that it may originate in the obscuring material (e.g. Yaqoob & Padmanabhan 2004; Shu, Yaqoob & Wang 2010). Moreover, the equivalent width (EW) of the Fe Kα line can be as large as several keV (e.g. Levenson et al. 2006) which may be a signature of Compton thick (CT) gas (e.g. Murphy & Yaqoob 2009). A correlation between the Fe Kα EW and the line-of-sight column density is observed for columns $>10^{23}$ cm$^{-2}$ indicating that the line is often produced by CT gas in the AGN environment (e.g. Guainazzi, Matt & Perola 2005; Fukazawa et al. 2010). Thus, the Fe Kα line can be used as an important proxy to study the properties of the obscuring gas around AGNs.

In recent years, there have been several Monte Carlo models of X-ray reprocessing from a CT torus (e.g. Ikeda, Awaki & Terashima 2009; Murphy & Yaqoob 2009; Brightman & Nandra 2011). However, all of these calculations omit dust from the models which in many cases may be present in the X-ray absorbing gas...
Finally, to study the effects of dust on the Fe Kα emission line, the EW of the line is analysed as a function of \( N_{\text{H}} \) and \( n_d \) for both sets of models. The EW is defined as the ratio of the intensity of the Fe Kα emission line \( (I_{\text{Fe Kα}}) \) to the reflected continuum at the line energy \( (I_c) \) multiplied by the energy bin width \( (\Delta E) \):

\[
EW = \frac{I_{\text{Fe Kα}}}{I_c} \times \Delta E.
\]

Ideally, \( I_c \) should be measured at 6.4 keV, but because of the presence of the emission line, it is difficult to determine \( I_c \) at that energy. Therefore, \( I_c \) is measured at 6.3 keV as there are no predicted emission lines at that energy. Using a different \( I_c \) between 6.3 and 6.5 keV leads to only very small changes in the EW. Rather than measuring \( I_{\text{Fe Kα}} \) from the predicted spectrum, we use the emergent line intensities reported in the \textsc{cloudy} output since it takes into account the effects of extinction on the line intensities. In the ND models, the Fe Kα emission line comes from cold gas (e.g. George & Fabian 1991; Weaver, Gelbord & Yaqoob 2001; Page et al. 2004; Yaqoob & Padmanabhan 2004; Zhou & Wang 2005; Jiang, Wang & Wang 2006; Levenson et al. 2006), and in the WD models it comes from both cold gas and grains which are added to obtain \( I_{\text{Fe Kα}} \). The cold Fe Kα fluorescence line defined by \textsc{cloudy} is actually emitted between 6.4 to 6.424 keV for Fe I to Fe X (House 1969); therefore, we set \( \Delta E = 24 \) eV in equation (1). As a consistency check, the EW calculation was compared with the result from Ikeda et al. (2009). Our results predict the ND Fe Kα EW to be \( \approx 1.8 \) keV for \( N_{\text{H}} = 10^{24} \) cm\(^{-2} \) and \( n_d = 10^7 \) cm\(^{-3} \) which is slightly lower than the EW \( \approx 2 \) keV predicted from the Monte Carlo simulations of Ikeda et al. (2009). However, given the differences in computational techniques and physical setup, this difference is adequate. In addition, we are focused on the relative changes in the EW when dust is included in the irradiated gas.

3 RESULTS

Fig. 1 shows how the Fe Kα EW depends on \( N_{\text{H}} \) and \( n_d \). The left-hand panel of Fig. 1, shows that the Fe Kα EW increases with \( N_{\text{H}} \) for Compton thin gas (10\(^{22} < N_{\text{H}} < 10^{28} \) cm\(^{-2} \)). Such a dependence is expected since the amount of illuminated gas increases with \( N_{\text{H}} \) and this produces more Fe Kα emission. For CT gas (10\(^{24} < N_{\text{H}} < 10^{28} \) cm\(^{-2} \)), the amount of gas irradiated by X-rays is limited by Compton scattering and the Fe Kα EW is fairly invariant with \( N_{\text{H}} \). In addition, the EW of Fe Kα increases with \( n_d \) in both the ND and WD models due to the rise in total opacity with \( n_d \). This reduces \( I_c \) and therefore increases the EW.

Our calculation shows that the presence of dust may significantly enhance the Fe Kα EW. The right-hand panel of Fig. 1 shows that the EW of the Fe Kα line is increased by a factor of 2.5 for \( n_{d} = 10^6 \) cm\(^{-3} \) (for \( N_{\text{H}} > 10^{24} \) cm\(^{-2} \)) due to the presence of grains. For \( n_d = 10^7 \) and \( 10^8 \) cm\(^{-3} \), the EW is enhanced by a factor of 4.1 and 8, respectively. To illustrate the reason for this enhancement, Fig. 2 plots \( I_c \) and \( I_{\text{Fe Kα}}/n_d \) ratios versus \( N_{\text{H}} \). This figure clearly shows that the change in EW between WD and ND is due to the reduction in the continuum and not because of a change in \( I_{\text{Fe Kα}} \). \( I_{\text{Fe Kα}} \) does slightly increase due to the presence of grains, but this is largely due to the abundances in the models ND and WD not being perfectly self-consistent; the Fe abundance is 5 per cent higher in WD models. Therefore, it is expected to have slightly more Fe Kα emission line in the case of WD.)

Fig. 2 shows the increase in EW of Fe Kα when reflected by dusty gas is due to a reduced continuum. This suppressed reflection continuum is due to the reduction in backscattering opacity (\( k_{b} \)).
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in dusty gas. Fig. 3 shows how $k_s$ varies inside the column of an illuminated gas as a function of depth for WD and ND models for $N_H = 10^{24} \text{cm}^{-2}$ and $n_H = 10^7 \text{cm}^{-3}$. At depths $>10^{13}$ cm, H is no longer ionized and dust contributes significantly to the scattering opacity; therefore, $k_s$ decreases significantly deep inside the cloud in WD models compared to the ND models. This drop in $k_s$ due to dust is because scattering from grains is highly anisotropic and favors scattering in the forward direction by an amount depending on the size, structure and shape of the grains (Draine 2003). Since the wavelength of X-rays is smaller than the size of most grains, there is only a weak coupling between the radiation and the grain leading to anisotropic scattering. As the Fe EW is computed using the backscattered continuum, this anisotropic scattering will reduce the backscattered intensity for WD models and thus the EW increases.

It has been proposed that dust in an AGN environment has fewer small grains than the typical ISM distribution (Maiolino 2001). As $k_s$ is proportional to grain size (Hayakawa 1970), a grain size distribution deficient in small grains will likely produce a stronger reflection continuum and thus the Fe Kα line will not increase as strongly as with the ISM grains. To check this effect, we computed a CLOUDY model ($n_H = 10^7 \text{cm}^{-3}$, $N_H = 10^{24} \text{cm}^{-2}$) with Orion abundances that includes a grain size distribution deficient in small grains. The $k_s$ from this model is overplotted on Fig. 3 to compare against the results from the ND and WD calculations. As expected, the Orion $k_s$ is larger than the one using ISM grains, but still smaller than the model with no dust. The EW of the Fe Kα line is enhanced by a factor of $\approx 4$ with the ISM grains, and by a factor of $\approx 2.6$ with the Orion grains. Hence, the anisotropic scattering behaviour of grains may still have an observable impact on the Fe Kα EW if the smaller grains are not present.

4 DISCUSSION AND SUMMARY

Many groups have computed two-dimensional X-ray reflection models for AGN torii without taking into account the effects of grains (e.g. Ikeda et al. 2009; Murphy & Yaqoob 2009; Brightman & Nandra 2011). However, it is possible that distant X-ray reflectors arise from dusty gas (Jaffe et al. 2004; Prieto et al. 2004, 2005; Meisenheimer et al. 2007; Tristram et al. 2007; Raban et al. 2009). Moreover, the Fe Kα line is an important proxy to estimate the column density of distant observing gas (Ghisellini, Haardt & Matt 1994). Therefore, we used CLOUDY to compute simple one-dimensional models of dusty gas illuminated by an AGN in order to study the effects of dust on Fe Kα emission line. We found that the presence of dust may significantly enhance the Fe Kα EW (by factors of $\approx 5$) in the reflection spectrum even in non-CT gas. When grains are present...
in the gas, scattering is anisotropic and there are less backscattered photons in the reflected continuum and the overall continuum intensity is decreased. This suggests that inferring a CT $N_H$ from the Fe Kα EW can be precarious.

The increase in EW occurs when dust dominates $k_\alpha$ and therefore will be most important when the gas contains predominantly neutral hydrogen. This limits the reflecting cloud to be relatively distant from the nucleus or to have a significant density. Therefore, the Fe Kα EW enhancement may only be important for a certain subset of AGNs that exhibit infrared emission from AGN heated dust, a large Fe Kα EW, and an unusually weak Compton reflection component. For example, NGC 7213 is observed to have significant hot dust emission (Ruschel-Dutra et al. 2010), an Fe Kα 120 eV and 24 eV and is observed to have $N_H$ from the Fe Kα line is a possibility (Bianchi et al. 2003), our results also suggest that reprocessing from the dusty Compton thin gas in the absorber may also contribute to the Fe Kα line.

We conclude that the anisotropic scattering behaviour of grains is an important mechanism to take into account when modelling X-ray reflection from tori since it may have a significant effect on the predicted Fe Kα EW. However, the effects of geometry are important. Since the scattering behaviour of grains directly affects the continuum, the effects of grains depends on the viewing angle relative to the orientation of torus; therefore, the true magnitude of the effect needs to be studied in multidimensional models. The EW of the emission line may be reduced, enhanced or unchanged since the continuum can be the transmitted spectrum, reflected spectrum, incident spectrum or their combination depending on the viewing angle.

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