A receding torus model for the Iwasawa-Taniguchi effect for Compton-thick AGN

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ABSTRACT

Recently, Boorman et al. (2018) reported on the discovery of the Iwasawa-Taniguchi (I-T) effect (a.k.a. X-ray Baldwin effect) for Compton-thick AGN. They measured a decrease of the 6.4 keV iron line equivalent width with the 12 μm luminosity, assumed as a proxy for the intrinsic X-ray luminosity, which in Compton-thick AGN is not directly observable. One of the most popular explanations of the classic I-T effect is the so-called receding torus model, i.e. the decrease of the covering factor of the molecular ‘torus’ with X-ray luminosity. In this paper we show that an I-T effect for Compton-thick AGN is indeed expected in the receding torus model, assuming that the torus is funneling the primary X-ray luminosity which is then scattered in a ‘hot mirror’. We found that the observed relation is well reproduced provided that the typical column density of the ‘hot mirror’ is about \(7.5 \times 10^{22} \text{ cm}^{-2}\).

Key words: galaxies: active – X-rays: galaxies

1 INTRODUCTION

In a recent paper, Boorman et al. (2018) reported on the discovery of the Iwasawa-Taniguchi (I-T) effect for Compton-thick AGN. The I-T effect, sometimes also referred to as X-ray Baldwin effect, is the decreasing of the 6.4 keV iron line equivalent width (EW) with X-ray luminosity, discovered by Iwasawa & Taniguchi (1993) and then confirmed in several other works (e.g. Page et al. 2004; Bianchi et al. 2007; Ricci et al. 2014). The classic I-T effect, which applies to the narrow component of the iron line which is likely produced by distant matter (e.g. the pc-scale ‘torus’), has been observed in unobscured sources, where the iron line EW is calculated with respect to the primary continuum. In Compton-thick AGN, however, the primary X-ray continuum is completely obscured by intervening matter, and the I-T effect observed by Boorman et al. (2018) is in fact against the 12 μm luminosity, assumed as a proxy for the intrinsic one. In such sources, the iron line EW is calculated with respect to the observed X-ray continuum, which is usually dominated by a reflection component from neutral matter (here-in-after “cold reflection”), likely the same matter where the iron line is originated. In this case, the line and the reflected continuum should scale in the same way with the intrinsic luminosity, and the line EW should therefore be independent of the latter parameter, if properties of the torus like the iron abundance are also independent of the intrinsic luminosity, and if the torus is always optically thick. The I-T effect for Compton-thick source is therefore, at a first glance, rather surprising.

Among the possible explanations, Boorman et al. (2018) mentioned a contribution, in the reflection continuum, by a ‘mirror’ of highly ionized matter (‘hot mirror’ here-in-after). In this paper, we explore further this hypothesis. Evidence of ionized reflection is clearly present in most obscured AGN, especially in soft X-rays. This matter may be related to the scattering mirror which polarizes the broad lines in several Seyfert 2 galaxies (Antonucci & Miller 1985; Antonucci 1993; Tran 2001). Now, one of the most popular explanations for the classical I-T effect is the receding torus model, in which the covering factor of the torus (and therefore the 6.4 keV iron line flux, which is produced in the torus after reprocessing of the primary emission) decreases with the luminosity (probably as a result of a dependence on the Eddington ratio, e.g. Bianchi et al. 2007, Zhuang et al. 2018, even if the latter authors find a reverse of this dependency for Eddington ratio larger than 0.5). Let us assume that the ionized gas acting as the hot reflector fills the opening part of the obscuring torus which naturally varies as the torus covering fraction changes, and that the hot mirror is illuminated by the intrinsic AGN radiation, which in turn is funneled by the torus. Under these assumptions, the relative importance of the hot reflection will increase with luminosity, providing a possible explanation for the I-T effect for Compton-Thick
AGN. In this way, the latter relation would be a natural consequence of the classic I-T effect.

In the following, we calculate the expected I-T Compton-Thick effect in the receding torus model under the above, simple assumptions. The scope of the paper is just to check if the proposed explanation could work, and under what conditions, so for simplicity we will use the observed I-T relations at their face values without considering the related uncertainties.

2 THE EXPECTED I-T EFFECT FOR COMPTON-THICK AGN IN THE RECEDING TORUS MODEL

The equivalent width of the iron line in Compton-Thick sources, $EW_{CT}$, where the primary emission is obscured and the continuum below the line is entirely due to the reflection components, is given by:

$$EW_{CT} = \frac{F_{\text{line}}}{F_{\text{CR}} + F_{\text{HR}}}$$

(1)

where $F_{\text{line}}$ is the iron line flux and $F_{\text{CR}}$ and $F_{\text{HR}}$ are the continua at 6.4 keV due to cold (torus) and hot (mirror) reflection, respectively.

On the other hand, Bianchi et al. (2007) established the I-T relation for unobscured AGN:

$$EW = \frac{F_{\text{line}}}{F_{\text{int}}} = A\alpha(L_\alpha)$$

(2)

where $F_{\text{int}}$ is the continuum flux at 6.4 keV due to the intrinsic radiation (which we assume to be, at that energy, dominant with respect to both reflection continua). $\alpha$ represents the luminosity-dependent fractional covering factor of the torus. $A$, therefore, is the EW for a covering factor of order unity, i.e. $\sim 110$ eV (e.g. Ghisellini, Haardt & Matt; Matt, Guainazzi & Maiolino 2003). From Bianchi et al. (2007), $\alpha$ can be written as $0.5L_{\alpha,44}^{-0.17}$, $L_{X,44}$ being the 2-10 keV luminosity normalized to $10^{44}$ erg/s. This implies that the relation holds only down to $L_{X,44} \sim 0.01$; below this value, it has to saturate, otherwise the covering factor would exceed unity.

The cold reflection component, being due to the same matter producing the iron line, should follow the same luminosity dependence, $F_{\text{CR}} = B\alpha(L_\alpha)F_{\text{int}}$, where $B$ is the ratio between reflected and intrinsic fluxes for a covering factor of order unity. In our model, the hot mirror is illuminated by the radiation funnelled by the torus, and therefore its covering factor is complementary to that of the torus itself. Therefore, the hot reflection component is given by $F_{\text{HR}} = C[1 - \alpha(L)]F_{\text{int}}$, where $C$ again is the ratio between reflected and intrinsic fluxes for a covering factor of order unity. Inserting in Eq. 1, and after simple algebra:

$$EW_{CT} = \frac{1}{\frac{1}{A} + \frac{1}{\alpha(L)} - \frac{1}{\alpha}}$$

(3)

Here, $B/A$ corresponds to $F_{\text{line}}/F_{\text{CR}}$ and is essentially the iron line equivalent width with respect to Compton reflection only, which we assume to be $\sim 1$ keV (e.g. Ghisellini, Haardt & Matt; Matt, Guainazzi & Maiolino 2003). At this point, the I-T effect for Compton-thick sources can be written as a function of the intrinsic luminosity, assuming a certain value for $C$, which is the fraction of scattered radiation from the hot mirror for a covering factor of 1, and thence represents the Thomson optical depth of the reflecting matter ($C=1$ would then correspond to a column density, $N_H$, of $\sim 1.5 \times 10^{24}$ cm$^{-2}$, but note that the relation strictly holds only for optically thin matter). The expected $EW_{CT}$ vs. intrinsic luminosity is shown in Fig. 1 (upper panel) for different choices of $C$.

The I-T effect found by Boorman et al. (2018) is, however, as a function of the 12 $\mu$m luminosity. In the lower panel of Fig. 1, the $EW_{CT}$ versus this luminosity is plotted, adopting the relation between nuclear (e.g. AGN-dominated) mid-infrared and X-ray luminosities reported by Gandhi et al. (2009) in their eq. 2.

3 DISCUSSION AND CONCLUSIONS

From Fig. 1, lower panel, it can be seen that a good agreement with the observed relation is found for $C=0.05$ ($N_H=7.5 \times 10^{22}$ cm$^{-2}$), even if the theoretical and observed curves tend to diverge at high luminosities, where however there are not many data points. Because $C$ is the scattering fraction for a covering factor of 1 of the hot mirror, this implies that the luminosity-dependent scattering fraction (which is the product of the opacity, which we assume to be the same for all sources, and the luminosity-dependent covering fraction) goes from 5% at very large luminosities down to fractions of percent for luminosities around $10^{42}$ erg/s, where the relation has to saturate, as mentioned in the previous section.

Not much is known about the scattering fraction of the hot mirror, observationally, due also to the difficulties, in Compton-thick sources at least, to assess the intrinsic luminosity. Moreover, contamination from thermal emission may be significant for low luminosity sources and/or in the presence of intense star-forming regions (e.g. Wang et al. 2014). A systematic study of the luminosity dependence of the hot mirror scattering efficiency would be required to test the model presented in this paper. At present, information is rather sparse. High values (3-6%) have been found in NGC 7674 (Gandhi et al. 2017), a source with an intrinsic $2-10$ keV X-ray luminosity likely in the $0.1 - 1 \times 10^{44}$ erg/s range. In NGC 1068, on the other hand, the value seems to be well below 1% (Matt et al. 2004), and the same is true for several other sources (e.g. Ueda et al. 2007; Comastri et al 2010; Eguchi et al. 2011). Ricci et al. (2017) measured this parameter in a handful of Swift-BAT selected sources finding values ranging from <0.7 to 2.

A potential problem is that ionized iron lines may also be produced in the hot mirror, increasing the 6.4 keV iron line equivalent width for the faintest sources for which a clear separation between neutral (6.4 keV) and ionized (6.7-7 keV) lines may be difficult even with CCD-like detectors. On the other hand, the presence of such lines may help explaining the flattening of the observed curve at high luminosities (and therefore, in our model, at high scattering fractions) with respect to the calculated one. He- and H-like iron lines have indeed been observed in some (but not all) Compton-thick AGN, most notably NGC 1068 (Iwasawa, Fabian & Matt 2010; Fabian et al. 2014). A systematic study of the luminosity dependence of these lines may be significant for low luminosity sources and/or in the presence of intense star-forming regions (e.g. Wang et al. 2014).

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Figure 1. The iron line equivalent width for Compton-thick sources as a function of the 2-10 keV luminosity (upper panel) and of the 12 µm luminosity (lower panel). The five curves refer to five values of $C=0.01, 0.03, 0.05, 0.07, 0.09$ (from top to bottom). The dashed line in the lower panel is the best-fit relation of Boorman et al. 2018. See text for details.

To summarize, we have shown that the receding torus model, often invoked to explain the classic I-T effect, may also naturally explain the recently discovered I-T effect for Compton-thick AGN (Boorman et al. 2018), provided that the hot mirror has typically a column density of $\sim 7.5 \times 10^{22}$ cm$^{-2}$. High quality, high energy resolution observations of Compton-thick sources are required to check the validity of our assumptions.

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REFERENCES

Antonucci R., 1993, ARAA, 31, 473
Antonucci R., Miller J.S., 1985, ApJ, 297, 621
Bauer F.E. et al., 2015, ApJ, 812, 116
Bianchi S., Guainazzi M., Matt G., Fonseca-Bonilla N., A&A, 467, L19
Boorman P.G., Gandhi P., Baloković M., Brightmann M., Harrison F., Ricci C., Stern D., 2018, MNRAS, 477, 3775
Comastri A., Iwasawa K., Gilli R., Vignali C., Ranalli P., Matt G., Fiore F., 2010, ApJ, 717, 787
Eguchi S., Ueda Y., Awaki H., Aird J., Terashima Y., Mushotzky R., 2011, ApJ, 729, 31
Gandhi P., Horst H., Smette A., Hönig S., Comastri A., Gilli R., Vignali C., Duschl W., 2009, A&A, 502, 457
Gandhi P., et al., 2017, MNRAS, 467, 4606
Ghisellini G., Haardt F., Matt G., 1993, MNRAS, 267, 743
Guainazzi M., et al., 1999, MNRAS, 310, 10
Iwasawa K., Taniguchi Y., 1993, ApJ, 413, L51
Iwasawa K., Fabian A.C., Matt G., 1997, MNRAS, 289, 443
Matt G., Brandt W.N., Fabian A.C., 1996, MNRAS, 280, 823
Page K.L, O’Brien P.T., Reeves J.N., Turner M.J.L., 2004, 347, 316
Ricci C., Ueda Y., Paltani S., Ichikawa K., Gandhi P., Awaki H., 2014, MNRAS, 441, 3622
Ricci C., et al., 2017, ApJS, 223, 17
Ross R.R., Fabian A.C., MNRAS, 261, 74
Tran H.D., 2001, ApJ, 554, L19
Ueda Y., et al., 2007, ApJ, 664, L79
Wang J., et al., 2014, ApJ, 781, 55

MNRAS 000, 1–4 (2018)
Zhuang M.-Y., Ho L.C., Shangguan J., 2018, ApJ, in press (arXiv:1806.03783)

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