IGR J16351−5806: another close by Compton-thick AGN

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ABSTRACT

IGR J16351−5806 has been associated with the Seyfert 2 galaxy ESO 137−G34, having been first reported as a high energy emitter in the third INTEGRAL/Imager on Board the INTEGRAL Satellite survey. Using a new diagnostic tool based on X-ray column density measurements versus softness ratios \( (F_{2−10{\text{keV}}} / F_{20−100{\text{keV}}}) \), we have previously identified this source as a candidate Compton-thick active galactic nuclei (AGN). In the present work, we have analysed combined XMM–Newton and INTEGRAL data of IGR J16351−5806 in order to study its broad-band spectrum and investigate its Compton-thick nature. The prominent \( \text{K}\alpha \) fluorescence line around 6.4 keV (EW > 1 keV) together with a flat 2–10 keV spectrum immediately point to a highly obscured source. The overall spectrum can be interpreted in terms of a transmission scenario where some of the high energy radiation is able to penetrate through the thick absorption and be observed together with its reflection from the surface of the torus. A good fit is also obtained using a pure reflection spectrum; in this case, the primary continuum is totally depressed and only its reflection is observed. An alternative possibility is that of a complex absorption, where two layers of absorbing matter each partially covering the central nucleus are present in IGR J16351−5806. All three scenarios are compatible from a statistical viewpoint and provide reasonable AGN spectral parameters; more importantly all point to a source with an absorbing column greater than \( 1.5 \times 10^{24} \text{ cm}^{-2} \), that is to a Compton-thick AGN. Because of this heavy obscuration, some extra components which would otherwise be hidden are able to emerge at low energies and can be studied; a thermal component with \( kT \) in the range 0.6–0.7 keV and free metal abundance is statistically required in all three scenarios while a scattered power law is only present in the pure reflection model. By providing strong evidence for the Compton-thick nature of IGR J16351−5806, we indirectly confirm the validity of the Malizia et al. diagnostic diagram.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

Compton-thick active galactic nuclei (AGN) are by definition those in which the X-ray obscuring matter has a column density equal to, or larger than, the inverse of the Thomson cross-section \( (N_H \geq \sigma_T^{-1} = 1.5 \times 10^{24} \text{ cm}^{-2}) \). The cross-sections for Compton scattering and photoelectric absorption have approximately the same value for energies of the order of 10 keV, which incidentally coincides with the lower energy threshold of hard X-ray telescopes like INTEGRAL/Imager on Board the INTEGRAL Satellite (IBIS) and Swift/Burst Alert Telescope (BAT). For columns in the range \( 10^{24} – 10^{25} \text{ cm}^{-2} \), the nuclear radiation is still visible above 10 keV and the source is called mildly Compton thick. For higher values of \( N_H \), the entire high energy spectrum is down-scattered by Compton recoil and hence depressed over the entire X/gamma-ray band. Generally, indirect arguments allow determination of the Compton-thick nature of an AGN, such as the presence of a strong iron K line complex at 6.4–7 keV and the characteristic reflection spectrum. The presence of Compton-thick matter can also be inferred through the ratio of isotropic versus anisotropic emission; primarily the \( L_X / L_{[\text{O III}]} \) ratio\(^1\) has been used in the literature to recognize Compton-thick sources (Bassani et al. 1999 and Panessa & Bassani 2002). There are various reasons why these AGN are important observational targets. They are a key ingredient of the cosmic X-ray background and, through their absorbed/re-emitted radiation, also of the IR one. The heavy obscuration present in these objects allows some spectral components which are otherwise usually hidden by the

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\(^1\) Where the \( L_{[\text{O III}]} \) is corrected for reddening in the host galaxy by means of the \( \text{Ha}/\text{H}\beta \) Balmer decrement.
nuclear emission to emerge and be studied in some detail. Despite their importance, studies of Compton-thick AGN have so far been hampered by the lack of high energy coverage in X-ray missions and subsequent difficulties in performing surveys above 10 keV. This situation has been changed by the advent of satellites like INTEGRAL and Swift, which are surveying a large fraction of the sky with good sensitivity and arcminute location. As a result, a number of Compton-thick candidates are now emerging and can be the subject of more in-depth studies (Comastri et al. 2007; Ueda et al. 2007; Sazonov et al. 2008). In particular, Malizia et al. (2007) studying a sample of 34 INTEGRAL AGN in the X-ray band, proposed a new diagnostic tool which allows the isolation of Compton-thick AGN candidates: this relies on measurement of the source X-ray column density and softness ratio defined as $F_{2-10 keV}/F_{20-100 keV}$. Using this tool, Malizia and coworkers suggested three INTEGRAL-detected AGN as Compton-thick candidates (IGR J14175−4641, IGR J16351−5806 and Swift J0601.9−8636) based on the apparent absence of an absorbing column density accompanied by a very low softness ratio. One of these sources, Swift J0601.9−8636, has subsequently been observed by Suzaku (Ueda et al. 2007) and found to be a Compton-thick AGN; the Suzaku spectrum revealed a heavily absorbed power law component with a column density of $N_H \sim 10^{24}$ cm$^{-2}$ and an intense reflection component with a solid angle $\geq 2\pi$ from a cold optically thick medium. In this paper, we present XMM–Newton and INTEGRAL data of IGR J16351−5806 which provide strong evidence for the Compton-thick nature of also this object and indirectly confirm the validity of the diagnostic diagram proposed by Malizia et al.

2 IGR J16351−5806 = ESO 137–G34

IGR J16351−5806 was first reported as a hard X-ray emitter by Bird et al. (2007) and subsequently confirmed by Krivonos et al. (2007). Here and in the following, we use data collected for the 3rd IBIS survey (Bird et al. 2007), which in this region correspond to a total exposure of $\sim$1.4 Ms. A clear excess is present in the 18−60 keV IBIS map with a significance of $\sim$8.3$\sigma$ at a position corresponding to RA(2000) = 16°35′11″04 and Dec.(2000) = −58°05′24″0 and with an associated uncertainty of 3.1 arcmin (90 per cent confidence level). Our position is compatible with that reported by Krivonos et al. (2007) (note that their 2.1 arcmin error radius corresponds to 68 per cent confidence level). The source position was then reduced to arcsec accuracy by means of Swift/X-Ray Telescope (XRT) observations which located the source at RA(J2000) = 16°35′13″17, Dec.(J2000) = −58°04′49″68 (5.1 arcsec uncertainty) and confirmed the association with the Seyfert 2 galaxy ESO 137−34 at $z = 0.009$ (Landi et al. 2007; Malizia et al. 2007).

ESO 137−34 is an S0/a galaxy which in Hubble Space Telescope (HST) images display a long dust lane east of the nucleus, running northwest–southeast, parallel to the photometric major axis of the galaxy and a second dust lane perpendicular to the first one (Ferruit, Wilson & Mulchaey 2000); moreover in the HST [O III] $\lambda$5007+[N II] $\lambda$6584+[H$\alpha$] map, the morphology of the central regions appears biconical.

The source was observed in the radio waveband with the Australia Telescope Compact Array (ATCA) telescope at 3.5 cm: it has a flux of 9.6 mJy and displays a complex morphology consisting of three knots aligned along a position angle of $−40^\circ$ (Morganti et al. 1999). The radio emission is coincident with the inner part of the line-emitting gas.

The source has been studied for the first time in X-rays by Malizia et al. (2007) using Swift/XRT observations, and its X-ray spectrum was broadly defined as being a flat ($\Gamma = 1.6$) power law with no absorption in excess of the Galactic value. The 2–10 keV observed flux is $3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ almost a factor of 100 weaker than the 20–100 keV flux measured by INTEGRAL (2 × $10^{-11}$ erg cm$^{-2}$ s$^{-1}$). IGR J116351−5806 was serendipitously observed by XMM–Newton on 2006 February 13, and these X-ray data together with the INTEGRAL ones are used in this work to study the broad-band (0.5–100 keV) spectrum of the source. This analysis provides evidence for the presence of features typical of a Compton-thick AGN.

3 DATA ANALYSIS

XMM–Newton EPIC-pn (Strüder, Briel & Dennerl 2001) data were reprocessed using the XMM Standard Analysis Software (SAS) version 7.1.2 employing the latest available calibration files. Only patterns corresponding to single and double events (PATTERN $\leq 4$) were taken into account; the standard selection filter FLAG = 0 was applied. The observation has been filtered for periods of high background and the resulting exposure is 17 ks. Source counts were extracted from circular region of radius 25 arcsec centred on the source in order to exclude the extended emission associated to the galaxy; background spectra were extracted from circular regions close to the source, or from source-free regions of 80′′ radius. The ancillary response matrices (ARFs) and the detector response matrices (RMFs) were generated using the XMM m1as tasks arfgen and rmfgen; spectral channels were rebinned in order to achieve a minimum of 20 counts for each bin. Fig. 1 shows the 4–10 keV pn image of the region surrounding IGR J16351−5806 with the INTEGRAL error box superimposed; it clearly shows that the AGN is the only source of hard X-ray photons and hence the counterpart of the INTEGRAL source. Inspection of the XMM light curve provides no evidence for variability over the observing period, so all data were used for the spectral analysis.

The INTEGRAL data reported here consist of several pointings performed by the IBIS/INTEGRAL Soft Gamma-Ray Imager (ISGRI) (Lebrun et al. 2003; Ubertini et al. 2003) instrument...
between revolution 12 and 429, that is, the period from launch to the end of 2006 April. ISGRI images for each available pointing were generated in various energy bands using the INTEGRAL Science Data Center (ISDC) off-line scientific analysis software OSA (Goldwurm et al. 2003) version 5.1. Count rates at the position of the source were extracted from individual images in order to provide light curves in various energy bands; from these light curves, average fluxes were then estimated and combined to produce an average source spectrum in the 20–110 keV band (see Bird et al. 2007 for details).

The XMM–Newton data have been fitted together with the INTEGRAL ones using XSPEC v.12.3.1; errors are quoted at 90 per cent confidence level for one parameter of interest ($\Delta \chi^2 = 2.71$). In the fitting procedure, a cross-calibration constant, $C$, between X- and gamma-ray data has been introduced and fixed to 1 since generally a good agreement between the two instruments has been found in previous works regarding various AGNs (De Rosa et al. 2008; Molina et al. 2008; Panessa et al. 2008). In the following analysis, we always include the Galactic column density which in the direction of IGR J16351–5806 is $N_{\text{H}} = 2.47 \times 10^{22} \text{cm}^{-2}$ (Dickey & Lockman 1990).

A simple absorbed power-law model fails to reproduce the broad-band spectrum of IGR J16351–5806: it gives a steep photon index ($\Gamma = 2.5$), no absorption and a $\chi^2$ of 607.11 for 93 d.o.f. However, if only the XMM data are considered over the 2–10 keV band, the photon index is much flatter ($\Gamma \ll 1$), there still is no evidence of absorption in excess to the Galactic value, and the observed 2–10 keV flux is $\sim 5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. This spectrum is similar to that observed in the prototype Compton-thick AGN NGC 1068 (Matt et al. 2000). Although the XMM spectrum is flatter than the XRT one (probably due to the different energy band used), the X-ray fluxes are compatible, suggesting no significant variation over 1 yr time-scale. The use of the XMM fit over a broader band (0.2–100 keV, see Fig. 2) helps in identifying extra features which contribute to the overall emission. Indeed, inspection of Fig. 2 indicates the presence of a strong soft excess and a prominent line at around 6.4 keV. These features, together with the flat photon index, strongly resemble a Compton-thick AGN.

The shape of the emission below 2 keV and the presence of emission lines clearly indicate the presence of gas photoionized by the central engine of the AGN (see discussion). This component is often present in Compton-thick AGN (Guainazzi et al. 1999, 2005) where, thanks to the high absorption, it emerges and can be well studied. It is generally fitted in XSPEC with a MEKAL model having free metal abundance. Indeed the addition of a MEKAL model improves the fit ($\Delta \chi^2 = 377$ for 2 d.o.f.) and gives a gas temperature $kT$ of 0.64$^{+0.04}_{-0.05}$ keV and, as already found in other absorbed AGN, a low metal abundance value $Z_0$ of 0.07$^{+0.03}_{-0.02}$ still leaving an extremely flat power law continuum ($\Gamma \sim 0.3$). Although this model yields an adequate fit to our spectrum, it is worth noting that it may be an oversimplified parameterization of the data. High resolution spectroscopy of nearby Seyfert 2s have, in fact, demonstrated that the soft X-ray emission is often dominated by emission lines with negligible contribution by an underlying continuum. Blending of these emission lines in the EPIC spectra can mimic a continuum emission (Iwasawa et al. 2003). As our main goal is to prove the Compton-thick nature of IGR J16351–5806, the uncertainties induced by a purely phenomenological modelling of the soft excess will not substantially affect the core results of our paper.

Another significant improvement ($\Delta \chi^2 = 105$ for 3 d.o.f.) is obtained when we introduce the K$\alpha$ iron fluorescence emission line: the energy of the line is found to be at 6.39 $\pm$ 0.02 keV with an equivalent width of about 2 keV. The intrinsic width of the line is narrow (0.09 $\pm$ 0.04) and for simplicity has been frozen to the observed value in subsequent fits. The flat slope of the power law ($\sim 0.3$) as well as the strength of the line at 6.4 keV (EW $\geq$ 1 keV) and the lack of absorption again suggest that the source is highly absorbed and likely to be in the Compton-thick regime (Matt et al. 2000).

Two models are generally used to account for the soft gamma-ray continuum of AGN in this regime.

(i) a transmission model more appropriate to mildly Compton-thick AGN; in this scenario the power law is absorbed by a column density in the range $10^{24} < N_{\text{H}} < 10^{25}$ and a Compton reflection component is often present and added to the fit (model MEKAL + WA$^*$ PO + ZGA + PEXRAV in XSPEC).

(ii) a pure reflection model more typical of Compton-thick AGN with $N_{\text{H}} > 10^{25}$ cm$^{-2}$; in this case the absorbed power law is no longer detected as it is totally absorbed and only the reflection component is visible (model MEKAL + PEXRAV + ZGA in XSPEC).

In order to evaluate the contribution of the Compton reflection component, we used the code developed by Magdziarz & Zdziarski (1995), where we fixed the cosine of the inclination angle to 0.5 and the cut-off energy at 1 MeV.

In the transmission scenario we find a column density of $N_{\text{H}} = 4.8 \times 10^{23}$ cm$^{-2}$, a photon index of 1.8 and a reflection of $\sim 1$ ($\chi^2 = 98.6/86$); it is worth noting that in this scenario the reflection component is highly requested as without it the model is unable to reproduce the INTEGRAL data.

The reflection model yields a good fit too (89.45/88): the high energy part of the spectrum is now represented by a reflection of 0.6 while the column density is indirectly estimated to be $N_{\text{H}} > 10^{25}$ cm$^{-2}$, that is a value typical of reflection dominated Seyfert 2 galaxies. In both models, the temperature and abundance of the thermal component are consistent while the iron line maintains an equivalent width around 1.5 keV. Both scenarios are able to explain such high values of EW and are therefore equally viable.

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2 This is the model also adopted by Ueda et al. (2007) to describe the Suzaku spectrum of Swift J0601.9–8636.
Table 1. Fit parameters.

|                | Transmission | Reflection | Complex abs |
|----------------|--------------|------------|-------------|
| $kT$ (keV)     | 0.69$^{+0.06}_{-0.04}$ | 0.66$^{+0.05}_{-0.05}$ | 0.62$^{+0.05}_{-0.05}$ |
| $N_{\text{H}}$ (cm$^{-2}$) | 4.8$^{+7.4}_{-1.6}$ $\times$ 10$^{24}$ | 3.7$^{+4.5}_{-1.5}$ $\times$ 10$^{24}$ | 0.31$^{+0.35}_{-0.19}$ |
| $C_{\text{f}}$ | -            | -          | 0.86$^{+0.09}_{-0.18}$ |
| $N_{\text{H}}$ (cm$^{-2}$) | -            | 5.8$^{+2.2}_{-2.2}$ $\times$ 10$^{23}$ | - |
| $C_{\text{f}}$ | -            | -          | 0.93$^{+0.08}_{-0.09}$ |
| $\Gamma_{\text{soft}}$ | -          | 2.42$^{+0.42}_{-1.60}$ | - |
| $\Gamma_{\text{hard}}$ | 1.82$^{+0.21}_{-0.27}$ | 1.33$^{+0.07}_{-0.07}$ | 1.78$^{+0.08}_{-0.07}$ |
| $E_{\text{break}}$ (keV) | 6.39$^{+0.02}_{-0.02}$ | 6.39$^{+0.02}_{-0.02}$ | 6.39$^{+0.02}_{-0.02}$ |
| $R$ | 1$^{+8.2}_{-0.82}$ | 0.59$^{+0.83}_{-0.59}$ | - |
| $E_{\text{in}}$ (keV) | -          | -          | 1.56$^{+0.28}_{-0.29}$ |
| $E_{\text{out}}$ (keV) | -         | 1.78$^{+0.08}_{-0.07}$ | 1.78$^{+0.08}_{-0.07}$ |
| $\chi^2$/d.o.f. | 98.59/86   | 89.45/86   | 88.70/85    |

*MEKAL + WA * PO + ZGA + PEXRAV.
*MEKAL + PO + PEXRAV + ZGA.
*MEKAL + PCFABS * PCFABS * PO + ZGA.

(Ghisellini, Haardt & Matt 1994). Despite the good fits, neither model (transmission or reflection) accounts for the excess counts in the range 2–5 keV which are still visible in the residuals and require the introduction of an additional component in the form of a power law. This addition is marginally required by the data in the transmission model (~90 per cent), while it is more significant in the reflection model (~99 per cent). If we assume that this extra component is due to scattered emission from the primary continuum, then the scattered fraction is around 6 per cent for the reflection model and 10 per cent for the transmission one; both values are similar to those typically observed in Seyfert 2 galaxies. If present, this soft component may be associated with the radio knots and emission line cones observed by ATCA and HST, or it could be due to soft emission from the galaxy and/or starburst activity in the source.

Note however that the addition of this extra component in the transmission model flattens the primary continuum ($\Gamma = 1.31^{+0.17}_{-0.10}$), gives a smaller column density ($N_{\text{H}} \sim 9 \times 10^{23}$ cm$^{-2}$) and has more difficulties in explaining a large iron line EW. On the basis of these indications, and in view of the marginal evidence in the data of this extra component, we prefer to neglect it in the transmission scenario but keep it in the reflection one; the relative best fit parameters for both models are given in columns 1 and 2 of Table 1.

We also consider an alternative scenario where IGR J16351–5806 is characterised by a complex absorption partially covering the central nucleus (MEKAL + PCFABS * PCFABS * PO + ZGA in XSPEC). This model mimics the reflection component and provides a canonical AGN spectrum ($\Gamma = 1.8$) for the source (see Table 1, Column 3). The absorption required by the data is in the form of two columns ($N_{\text{H1}} \sim 4 \times 10^{23}$ cm$^{-2}$ and $N_{\text{H2}} \sim 6 \times 10^{23}$ cm$^{-2}$), both covering 80–90 per cent of the source. Also in this case the combinations of such high columns are able to explain the observed iron line EW (Ghisellini et al. 1994).

Despite being rarely used in the literature to model Compton-thick AGNs, this model is of interest in view of recent studies on the torus geometry and nature which strongly indicate that this structure is clumpy and made of dusty clouds that are individually optically thick (Elitzur 2008). It is possible that in IGR J16351–5806, the torus is stratified with a Compton-thick region which progressively decreases in column density moving away from its plane; in this case two layers with different absorption (one Compton thick and one Compton thin) are intercepted by our line of sight (Risaliti et al. 2005); if this is the case, variations in the column densities are expected as the clouds move through these two regions. Besides giving the best $\chi^2$ (88.7/85) of all 3 models used here, the complex absorption scenario is also attractive for its simplicity as it does not require additional spectral features such as the reflection and the extra power law components. Although further X-ray observations of the source can confirm or deny the presence of a complex absorber by measuring variations in the column densities, we tentatively assume this to be the more appropriate scenario for this source. The unfolded spectrum of IGR J16351–5806 fitted with this model is shown in Fig. 3.

4 DISCUSSION AND CONCLUSIONS

In this work, we have analysed the combined XMM–Newton and INTEGRAL–IBIS data of the Seyfert 2 galaxy IGR J16351–5806. The broad-band spectrum of IGR J16351–5806 provides immediate strong indications of its Compton-thick nature, in particular the presence of a flat 2–10 keV spectrum and of a prominent emission line around 6.4 keV. The overall spectrum can either be interpreted in terms of a transmission scenario where some of the high energy radiation is able to penetrate through the thick absorption and be observed together with its reflection from the surface of the torus. A good fit is also obtained using a pure reflection spectrum: in this case the primary continuum is totally depressed and only its reflection is observed. An alternative possibility is that of complex absorption, where two layers of absorbing matter each partially covering the central nucleus, are present in IGR J16351–5806. All three scenarios are compatible with the data from a statistical view point, provide reasonable AGN spectral parameters, and are capable of producing the observed iron line EW. They are therefore indistinguishable using the present data set, although the complex absorption model is more attractive for its simplicity and its geometrical implications for the torus that are more in line with recent observational and theoretical findings. Whether mildly absorbed, totally hidden
Because of this heavy obscuration, some extra components which would be otherwise hidden, are able to emerge at low energies and can be studied; this includes the presence of thermal emission with free metal abundance and possibly of a scattered power law. The presence in the soft X-ray band of a hot diffuse gas with $kT \sim 0.6–0.7$ and $A_Z > 0.05$ is in agreement with observational evidence coming from grating instruments onboard Chandra and XMM–Newton on other Compton-thick Seyfert 2 galaxies (Guainazzi et al. 2005): within the sample analysed by these authors similar temperature and abundance values were found and interpreted in terms of emission from an optically thin, collisionally ionized plasma. Although this could also be the interpretation in the case of IGR J16351–5806, we note the model used to fit the soft part of the spectrum of IGR J16351–5806 is still oversimplified and we need RGS data for a more detailed analysis; unfortunately the source is too weak for good quality RGS data in the present observation and needs to be re-observed with a longer exposure.

IGR J16351–5806 has been highlighted previously by Malizia et al. (2007) as one of three possible Compton-thick objects, using a new diagnostic tool based on the measurement of the X-ray column density and softness ratio $F_{2–10\text{keV}}/F_{20–100\text{keV}}$. Of their three candidates, SWIFT J0601.9–8636, has been subsequently confirmed as a Compton-thick AGN thanks to Suzaku observations (Ueda et al. 2007), another, IGR J14175–4641 is very dim and with too limited spectral information below 10 keV to be properly studied – we hope to overcome this with a future XMM pointing. The third source is IGR J16351–5806 discussed here. By proving its Compton-thick nature, we have also indirectly demonstrated the validity of the Malizia et al. (2007) diagnostic diagram and provided an extra tool in the search for such rare AGN. The use of this diagnostic together with other information will be further tested on a larger INTEGRAL AGN sample for which 2–10 keV data are now becoming available.

ACKNOWLEDGMENTS

We acknowledge ASI financial and programmatic support via contracts I/008/07/0 and I/088/06/0. The authors would like to thanks the anonymous referee for his/her help in suggesting the complex absorption as a possible scenario for IGR J16351-5806.

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