Nuclear obscuration in the high-ionization Seyfert 2 galaxy Tol 0109–383


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ABSTRACT

We report on the BeppoSAX detection of a hard X-ray excess in the X-ray spectrum of the classical high-ionization Seyfert 2 galaxy Tol 0109–383. The X-ray emission of this source observed below 7 keV is dominated by reflection from both cold and ionized gas, as seen in the ASCA data. The excess hard X-ray emission is presumably caused by the central source absorbed by an optically thick obscuring torus with \( N_H \sim 2 \times 10^{24} \text{ cm}^{-2} \). The strong cold X-ray reflection, if it is produced at the inner surface of the torus, is consistent with the picture where much of the inner nucleus of Tol 0109–383 is exposed to direct view, as indicated by optical and infrared properties. However, the X-ray absorption must occur at small radii in order to hide the central X-ray source but leave the optical high-ionization emission-line region unobscured. This may also be the case for objects such as the Seyfert 1 galaxy Mrk 231.

Key words: galaxies: individual: Tol 0109–383 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

It is widely accepted that obscuration is the key to explaining the Seyfert 2 properties in active galaxies (Antonucci 1993). However, the obscuring material in Seyfert 2 nuclei might take various forms or have a complex structure, and its distribution appears to be spread over a wide range of radii (e.g. subparsec to a few hundred parsecs), as argued by several authors (e.g. Malkan, Gorjian & Tam 1998; Taniguchi & Murayama 1998; Matt 2000). Depending on the observational techniques employed, the obscuration inferred of an active nucleus could be different. In particular, optical/near-infrared results often differ from X-ray results (e.g. Goodrich, Veilleux & Hill 1994) as they probe different phenomena taking place at different optical depths. This can, in turn, be used to investigate the structure of obscuration in Seyfert 2 nuclei.

The obscuring matter illuminated by a hidden active nucleus in Seyfert 2 galaxies is an important source of emission over a wide range of wavelengths. While dust reradiation in the far-infrared and some strong optical emission lines, such as [OIII] \( \lambda 5007 \), are considered to be isotropic, any illuminated surface of the obscuring matter could be viewing-angle dependent if it is in the form of a torus (Heckman 1995). High-ionization emission lines (Pier & Voit 1995; Murayama & Taniguchi 1998), hot \( (T_{\text{eff}} \sim 1000 \text{ K}) \) dust emission in the mid-infrared (e.g. Pier & Krolik 1992; Murayama, Mouri & Taniguchi 2000) and X-ray reflection (Ghisellini, Matt & Haardt 1994) are among the observables expected from an illuminated inner surface of an optically thick torus. These are therefore potential indicators of orientation of the obscuring matter in Seyfert 2 nuclei. Heisler, Lumsden & Bailey (1997) also argued that the detectability of polarized broad-line regions (PBLR) in Seyfert 2 nuclei is related to our viewing angle of the obscuring torus (see also Taniguchi & Anabuki 1999). X-ray data such as that obtained from BeppoSAX and ASCA have proved to be a powerful probe of heavily obscured active nuclei.

2 TOL 0109–383 (=NGC 424)

Tol 0109–383 is a southern early-type spiral galaxy at a redshift of 0.0117 (da Costa et al. 1991). This galaxy hosts one of the brightest
Seyfert 2 nuclei, exhibiting a very high ionization optical spectrum, inferred by the presence of [Fe vi]λ6087, [Fe x]λ6374 and [Fe xiv]λ5303 (Fosbury & Sansom 1985; Durret & Bergeron 1988; Murayama, Taniguchi & Iwasawa 1998). The high ionization region of Tol 0109–383 traced by [Fe x]λ6374 has been found to extend up to 5 arcsec (corresponding to 1.1 kpc for the source distance of 45.3 Mpc1) in radius (Murayama et al. 1998), although most (~70 per cent) of the emission is concentrated in the inner 1 arcsec (220 pc) in radius.

An obscured Seyfert 1 nucleus has been suggested for the nuclear activity in Tol 0109–383 (e.g. Boisson & Durret 1986). Broad Balmer emission has been detected in polarized light (Moran et al. 2000) and in direct light (Boisson & Durret 1986; Murayama et al. 1998). Permitted Feii, which is often seen in the spectra of Seyfert 1 galaxies but rarely seen in Seyfert 2 nuclei, has also been detected (Murayama et al. 1998). The reddening to the narrow-line regions (NLR) has been estimated to be AV = 1.4–2.0 (Fosbury & Sansom 1983; Durret & Bergeron 1988; Murayama et al. 1998) based on the Balmer decrement, which is comparable to the mean value (AV = 1.1) for Seyfert 2 galaxies (De Robertis & Osterbrock 1986). The Hubble Space Telescope/Wide Field Planetary Camera 2 (HST/WFPC2) image shows clear evidence for a dust lane running across the central part of the galaxy (Malkan et al. 1998). This could provide an obscuring screen in front of the nuclear region.

The radio power (e.g. log P20 cm = 22 W Hz−1, Ulvestad & Wilson 1989), infrared luminosity (LIR = 1041 erg s−1, or 3.4 × 1041 L⊙, IRAS FSC) and weak ultraviolet (UV) luminosity (LUV = 19.9 × 1041 erg s−1, a 100 Å-wide band IUE measurement from Mulchaey et al. (1994)) are typical of Seyfert 2 galaxies. A notable property is the very warm IRAS colour (e.g. S60/S25 = 1.0), indicating the presence of hot dust. Also, the small size of the radio source, which is only slightly resolved with VLA at 6 and 20 cm, Ulvestad & Wilson 1989; at 3.6 cm, Threau et al. 2000) and ATCA (at 3.5 cm, Morganti et al. 1999), is not typical of Seyfert 2 galaxies. Detection of soft X-ray emission with the Einstein Observatory (Green, Anderson & Ward 1992) and ROSAT (Rush et al. 1996; Voges et al. 1999) has been reported. However, the origin of the soft X-ray emission has not been clear (Murayama et al. 1998). Prior to the present paper, Collinge & Brandt (2000) analysed the ASCA data and concluded that Tol 0109–383 is a Compton-thick source.

### 3 Observations and Data Reductions

Tol 0109–383 was observed with ASCA (Tanaka, Inoue & Holt 1994) on 1997 July 2, and subsequently with BeppoSAX (Boella et al. 1997a) on 1999 July 26–28. Details of the observations are summarized in Table 1.

The four detectors on board ASCA, the Solid-State Imaging Spectrometers (SIS; S0 and S1) and the Gas Imaging Spectrometers (GIS; G2 and G3), were operating normally. The Seyfert galaxy was centred at the nominal position on the best-calibrated charge-coupled device (CCD) chips of each SIS detector (S0/C1 and S1/C3). Standard Revision-2 calibration and data reduction technique were employed, using ftools version 4.2 provided by the ASCA Guest Observer Facility at NASA’s Goddard Space Flight Center. The Seyfert galaxy is the brightest source in the detector field of view and there is no other source contaminating the source extraction region in each detector. Background data were taken from a source-free region on the same detector in the same observation. A significant decrease in efficiency of the SIS in the soft X-ray band has been reported in ASCA observations carried out after 1994 (ASCA GOF 1999). The detector responses used here have not been corrected for this effect, but for a faint source such as Tol 0109–383, the statistical error overwhelms the systematic error in the responses so that the results presented in this paper is not seriously affected.

The BeppoSAX observation provides a data set from three detectors; the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997), the Medium Energy Concentrator Spectrometer (MECS, Boella et al. 1997b) and the Phoswitch Detector System (PDS, Frontera et al. 1997). The data from each detector obtained through standard data reduction provided by the SAX Data Centre are used. The background data for the LECS and MECS were taken from the deep blank field observations while the off-source data during the observation are used as the background for the PDS which is a collimated instrument rocking between on- and off-source positions.

We quote in this paper values of X-ray flux obtained from the ASCA GIS and BeppoSAX MECS, for which the absolute flux calibration is reliable; indeed the two detectors are in good agreement with each other. The ASCA SIS agrees with the GIS in spectral shape but shows a few per cent smaller normalization than the GIS. The standard relative normalization factor 0.86 is assumed for the PDS. The normalization factor found for the LECS is ~0.7, which is within a reasonable range.

### 4 X-Ray Spectrum

#### 4.1 Broad-band X-ray spectrum

Fig. 1 shows the data from all the detectors of BeppoSAX and ASCA, divided by a power law with a photon index of \( \Gamma = 2 \), to demonstrate the broad-band spectral structure of Tol 0109–383. The photon index \( \Gamma = 2 \), typical of Seyfert nuclei and quasi-stellar objects.
Obscured nucleus of Tol 0109–383

4.2 The ASCA data

As Fig. 1 shows, the 0.6–3 keV spectrum can be described roughly with a power law of $\Gamma \approx 2$. Although a simple power-law fit provides a reasonably good fit ($\chi^2 = 64.0$ for 68 degrees of freedom with $\Gamma = 2.1 \pm 0.3$) to the SIS data, possible line-like features can also be seen (Fig. 2). Only a feature at 0.87 ± 0.04 keV is detected with over 90 per cent significance according to the F-test when a narrow Gaussian is fitted, while the other two features at 1.32 ± 0.06 and 1.86 ± 0.16 keV are less significant. The equivalent widths of these line features range between 80 and 140 eV. The 0.87 keV feature can be caused by a OVIII recombination continuum [see Griffiths et al. (1998) for a similar feature in the ASCA spectrum of Mrk 3 where they inferred $\xi \sim 500$ for the reflecting matter] or part of the Fe–L blend (e.g. FeXVII). The features at 1.32 and 1.86 keV are consistent with recombination lines from Mg xi (1.34 keV) and Si xiii (1.85 keV), respectively. These features in the soft X-ray band could also originate from thermal emission form a starburst. However, the optical and infrared properties of this object suggest that starburst activity is weak even if it is present.

The Fe K line is found at a rest-energy of 6.37 ± 0.03 keV. No significant broadening is found (the 90 per cent upper limit is 110 eV in the Gaussian dispersion, $\sigma$). The line flux is $3.1_{-0.3}^{+0.6} \times 10^{-3}$ photon s$^{-1}$ cm$^{-2}$, and the corresponding equivalent width is $=1.1$ keV with respect to the neighbouring flat continuum.

As mentioned in the previous section, the ASCA spectrum can be described with a sum of reflections from cold and ionized matter (also see Matt et al. 2000). The Fe K-band spectrum is well explained by reflection from thick, cold matter. The hard continuum fits well the reflection spectrum of pexrav. The soft X-ray emission-line features could originate from photoionized gas which also reflects a small fraction of the continuum light of the hidden central source. In this case, the photoionized gas should be optically thin, and the ionization parameter $\xi \sim$ few hundred.

Reflection from mildly ionized, optically thick matter is a possible alternative to explain the whole ASCA band spectrum, as proposed for the Circinus Galaxy (Bianchi, Matt & Iwasawa 2001). Note that the Fe K line remains at 6.4 keV and some excess soft X-ray emission is produced when $\xi \leq 30$. However, this possibility does not appear to be the case in Tol 0109–383. We have compared the $\xi = 30$ reflection spectrum of Ross, Fabian & Young (1999) with the data. The data above 3 keV are too hard to match the model spectrum, indicating that the Fe K-band emission is produced in matter significantly less ionized than $\xi = 30$. Therefore, a combination of reflection both from cold and highly ionized gas is more likely.
4.3 The BeppoSAX data

The data obtained from LECS and MECS are in good agreement with the ASCA data below the Fe K-band. The MECS data show a higher centroid energy of $6.63 \pm 0.09 \text{ keV}$ with significant broadening ($\sigma = 0.22^{+1.12}_{-0.11} \text{ keV}$) for the Fe K line. A slightly higher line intensity of $2.6^{+1.0}_{-0.8} \times 10^{-5} \text{ photon s}^{-1} \text{ cm}^{-2}$ is also obtained. A likely cause of the line broadening would be a blend of a 6.4-keV line and a higher ionization line, for example, FeXXV (6.7 keV), which should be resolved with the ASCA SIS, owing to the higher spectral resolution than the MECS and the GIS. However, no evidence for higher-energy lines is found in the ASCA data. This could be due to the gain shift problem with the MECS, although the offset is larger than that usually found (see, e.g., Dupke & Arnaud 2001). Another possible reason for this is the spectral resolution, which is not suitable for a complicated spectrum with a sharp drop on the higher-energy side of the line owing to the Fe K absorption edge. This could shift the line centroid to higher energy in a low-resolution detector. A spectral analysis of the data from the ASCA GIS only, which is a similar detector to the MECS, gives the line energy of $6.44^{+0.17}_{-0.10} \text{ keV}$. The large error for the GIS line energy towards higher energies is suggestive but not conclusive enough to settle the problem. Since a narrow line at 6.4 keV is more plausible on physical grounds given the continuum shape, and an unexpected gain drift in the detector could lead to line broadening, we are cautious about an immediate interpretation of the discrepancy.

![Figure 3](https://example.com/f3.png)

Figure 3. Upper panel, the ASCA data from the four detectors and the BeppoSAX PDS data of Tol 0109–383, fitted by the model consisting of cold and warm reflection and a strongly absorbed power law. Gaussian lines at the rest-energies of 0.87, 1.34, 1.86 and 6.4 keV are also included. Middle panel, the BeppoSAX LECS, MECS and PDS data of Tol 0109–383, fitted with the same model as above apart from the absorption column density and iron K line parameters (see text). Lower panel, the best-fitting model for the ASCA+PDS data, consisting of components given in Table 2.

5 DISCUSSION

The ASCA spectrum is consistent with a reflection-dominated emission, as concluded by Collinge & Brandt (2000). The BeppoSAX PDS detection of a transmitted component at higher energies allows us to measure the column density of the Thomson thick absorber ($N_H \sim 2$–3 $\times 10^{23}$ cm$^{-2}$, or Thomson depth $\tau_T \sim 2$, assuming Solar abundance). The best estimate of the absorption-corrected 2–10 keV luminosity of the central source is $7 \times 10^{38} \text{ erg s}^{-1}$ for our assumed source distance. With the flattest
and the absorption-corrected continuum) in the 2–10 keV band, subtending at 2\(\mu\)m means that a quarter to half of the reflection expected from a slab holds for the distance-limited spectropolarimetric survey sample of Heisler et al. (1997) tends to have warm and moderately inclined obscuring torus is preferred for detecting emission has been detected even in the direct light in Tol 0109–383 (Moran et al. 2000). Note that broad Balmer emission has been detected in Tol 0109–383 (Murayama et al. 1998). Several authors have argued that a moderately inclined obscuring torus is preferred for detecting PBLR (e.g. Heisler et al. 1997; Taniguchi & Anabuki 1999). The PBLR Seyfert 2 sample of Heisler et al. (1997) tends to have warm IRAS colours, which is naturally explained by the viewing angle effect, i.e. hot dust at inner radii is more visible in a more inclined system (e.g. Pier & Krolik 1992). We have verified that this trend holds for the distance-limited spectropolarimetric survey sample of Moran et al. (2000). Awaki et al. (2000), however, prefer a large size of the scattering regions to the viewing angle effect for detectability of the PBLR.

For Tol 0109–383, the viewing angle appears to be an important key. The observed properties listed below all point to us looking into the inner part of the active nucleus:

limit of the spectral slope of the central source, \(\Gamma = 1.5\), this value is a factor of 2 larger. Note that the correction for Compton scattering (Matt et al. 1999) has been made (\(\gamma = 1\) for a spherical obscuration; the value increases to \(\sim 3\) if the covering fraction is small for \(N_H = 3 \times 10^{24} \text{cm}^{-2}\)).

The reflected fraction (i.e. the luminosity ratio of the observed and the absorption-corrected continuum) in the 2–10 keV band, where most of the observed flux comes from cold reflection, is \(\sim 5\gamma^{-1}\) per cent. Compared with the albedo from cold matter, this means that a quarter to half of the reflection expected from a slab subtending at 2\(\pi\) is visible to us. If the cold reflection occurs at the inner surface of the obscuring torus, then a large fraction of the surface is exposed to our view.

The optical polarization of the nucleus of Tol 0109–383 is relatively high (1.5 per cent, Brindle et al. 1990; 2.3 per cent, Moran et al. 2000 in the V-band) and polarized broad emission lines have been detected (Moran et al. 2000). Note that broad Balmer emission has been detected even in the direct light in Tol 0109–383 (Moran et al. 1998). Several authors have argued that a moderately inclined obscuring torus is preferred for detecting PBLR (e.g. Heisler et al. 1997; Taniguchi & Anabuki 1999). The PBLR Seyfert 2 sample of Heisler et al. (1997) tends to have warm IRAS colours, which is naturally explained by the viewing angle effect, i.e. hot dust at inner radii is more visible in a more inclined system (e.g. Pier & Krolik 1992). We have verified that this trend holds for the distance-limited spectropolarimetric survey sample of Moran et al. (2000). Awaki et al. (2000), however, prefer a large size of the scattering regions to the viewing angle effect for detectability of the PBLR.

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### Table 2

<table>
<thead>
<tr>
<th>Spectral components</th>
<th>Model</th>
</tr>
</thead>
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<tr>
<td>Soft X-ray emission</td>
<td>Power law ((\Gamma = 2.0))</td>
</tr>
<tr>
<td>Cold reflection</td>
<td>3 narrow Gaussian lines (at 0.87, 1.36 and 1.86 keV)</td>
</tr>
<tr>
<td>Absorbed central source</td>
<td>A Gaussian line (Fe K); see the separate table</td>
</tr>
<tr>
<td>Fe K line</td>
<td>Cold absorption:</td>
</tr>
<tr>
<td>Measurements</td>
<td>(N_H = 1.6^{+1.0}_{-1.0} \times 10^{24} \text{cm}^{-2}) (ASCA + PDS)</td>
</tr>
<tr>
<td></td>
<td>(N_H = 3.5^{+1.2}_{-1.2} \times 10^{24} \text{cm}^{-2}) (SAX)</td>
</tr>
<tr>
<td>Energy (keV)</td>
<td>Line width (keV)</td>
</tr>
<tr>
<td>Line flux (photons cm(^{-2}) s(^{-1}))</td>
<td>Quality of fit</td>
</tr>
<tr>
<td>Quality of fit</td>
<td>(\chi^2/\text{dof})</td>
</tr>
<tr>
<td>ASCA</td>
<td>6.37 ± 0.03</td>
</tr>
<tr>
<td>BeppoSAX</td>
<td>6.63 ± 0.09</td>
</tr>
</tbody>
</table>

### Table 3

<table>
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<tr>
<th>Galaxy name</th>
<th>Class</th>
<th>[Fe vii]/[O iii]</th>
<th>(S_{60}/S_{25})</th>
<th>(R(L, 25))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tol 0109–383</td>
<td>PBLR</td>
<td>5.36 \times 10^{-2}</td>
<td>1.03</td>
<td>-0.036</td>
<td>1, 6, 8</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>PBLR</td>
<td>1.87 \times 10^{-2}</td>
<td>2.07</td>
<td>-0.79</td>
<td>2, 6, 9</td>
</tr>
<tr>
<td>NGC 7674</td>
<td>PBLR</td>
<td>1.59 \times 10^{-2}</td>
<td>2.94</td>
<td>-0.76a</td>
<td>2, 6, 9</td>
</tr>
<tr>
<td>IRAS 09104+4109</td>
<td>PBLR</td>
<td>1.95 \times 10^{-2}</td>
<td>1.57</td>
<td>-1.25a</td>
<td>4, 5, 6</td>
</tr>
<tr>
<td>Circinus galaxy</td>
<td>S2</td>
<td>1.69 \times 10^{-2}</td>
<td>4.31</td>
<td>-1.16a</td>
<td>2, 7, 9</td>
</tr>
<tr>
<td>NGC 5643</td>
<td>S2</td>
<td>-</td>
<td>5.34</td>
<td>-1.26</td>
<td>2, 6, 8</td>
</tr>
<tr>
<td>ESO 138-G1</td>
<td>S2</td>
<td>2.71 \times 10^{-2}</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Mrk 231</td>
<td>S1</td>
<td>-</td>
<td>3.69</td>
<td>-0.53</td>
<td>6, 9</td>
</tr>
</tbody>
</table>

\(^{\dagger}\)Contamination from the host galaxy is likely.

\(^{\dagger}\)The \(L\)-band photometry is approximated by the \(L'\) data.
(i) the relatively large X-ray reflection fraction from cold matter, as discussed above;
(ii) the detection of broad Balmer emission and permitted Fe II emission in direct light (Murayama et al. 1998);
(iii) the very warm IRAS colour (see Table 3); and
(iv) the presence of high-ionization emission lines, particularly the high [Fe v]/[O III] λ5007 ratio (see Table 3).

As mentioned in the Introduction, some high ionization emission lines may originate in the inner surface of the optically thick torus (e.g. Pier & Voit 1995; Murayama & Taniguchi 1998), thus could be an indicator of the torus viewing angle. Nagao, Taniguchi & Murayama (2000) have shown that the [Fe v]/[O III] ratio is markedly different between the two types of Seyferts. A good segregation is also seen with the mid-infrared flux ratio of 3.5 μm (L-band) and 25 μm (Murayama et al. 2000). The IRAS S25/S25 ratio may not necessarily be a good indicator of torus orientation (Fadda et al. 1998; Murayama et al. 2000; Alexander 2001) since there must be a significant contribution to the 60-μm flux from the host galaxy, although Heisler et al. (1997) show that the PBLR and non-PBLR Seyfert-2 galaxies are well separated using this ratio.

We show the values of possible orientation measures mentioned above ([Fe v]/[O III] ratio, S25/S25 and R(L, 25) = \log\left(\frac{S_{\text{25}}}{S_{\text{25}}}\right) of Tol 0109–383 along with other Compton-thick Seyfert galaxies (Collinge & Brandt 2000; Matt et al. 1997, 1999; Risaliti, Maiolino & Salvati 1999; Malaguti et al. 1998; Iwasawa, Fabian & Ettori 2000; Maloney & Reynolds 2000), some of which have been known as PBLR Seyfert 2s, in Table 3. Two other Compton-thick sources, NGC 4945 and NGC 6240, are not included, since a starburst dominates the optical to mid-infrared bands in those galaxies. The high [Fe v]/[O III] ratio and the flat infrared spectrum, implied from the small S25/S25 and large R(L, 25) of Tol 0109–383 are consistent with a picture that the interior of the torus is largely exposed, compared with the other Compton-thick Seyfert 2s. The lack of correlation between the X-ray absorption column density (Bassani et al. 1999) and the [Fe v]/[O III] ratio (Nagao et al. 2000) probably means that the structure of obscuring tori in Seyfert 2 galaxies is not unique.

Despite the close resemblance to a Seyfert 1 nucleus, the central X-ray source in Tol 0109–383 is hidden behind heavy obscuration. The large column of absorbing gas is unlikely to be associated with the dust lanes imaged by the HST (Malkan et al. 1998). This is clearly a geometrical effect and the X-ray absorption is likely to occur on small radii, perhaps on the parsec scale, as originally proposed by Krolik & Begelman (1988) and also by Matt (2000). More exposure of an optical Seyfert 1 nucleus is found in Mrk 231, for which an X-ray nucleus hidden by a Compton-thick absorber has been suggested by Maloney & Reynolds (2000). The location of very thick X-ray absorbing matter may be distinct from the torus hiding the BLR (or an optical nucleus in Seyfert 2 galaxies), and could be in a special form (e.g. Elvis 2000).

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