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QUERYING FOR HEAVILY OBSCURED AGN VIA HIGH 9.7μm OPTICAL DEPTHS: RESULTS FROM THE 12μm, GOODS, AND FLS SPITZER SPECTROSCOPIC SAMPLES

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Abstract. To optimally identify candidates of the Compton-thick (CT) active galactic nuclei (AGN) that contribute to the unresolved X-ray background in infrared surveys, a tracer of column density is desirable in addition to an AGN indicator. In a recent study, we aimed to test whether the 9.7μm silicate absorption feature can be used for this purpose when seen at high optical depths. We found that the extreme criterion of optical thickness at 9.7μm is efficient in identifying CT objects among local AGN. Having identified six of the nine CT AGN in the 12μm sample with *Spitzer* and X-ray spectra, we expanded this analysis at intermediate/high z, using all GOODS and FLS sources with *Spitzer* and X-ray observations. We found 12 sources with $\tau_{9.7}$>1 that host an AGN between 0.8<z< 2.7. Four of them are likely to be CT according to their low X-ray to 6 μm luminosity ratio. Surveys with complete coverage in both mid-infrared spectra and X-ray data can provide large populations of such sources, as at least 5-9% of all infrared bright galaxies in the GOODS and FLS samples are $\tau_{9.7}$>1 AGN.

Keywords: galaxies: active, infrared: galaxies, X-rays: galaxies

1 Introduction

Observational evidence points out to the existence of a population of active galactic nuclei (AGN) that is yet unidentified due to extreme dust obscuration. The observed space density of black holes in the local Universe cannot be accounted for, unless AGN with column densities of $>10^{24}$ cm^{-2} exist (Comastri 2004; Merloni & Heinz 2008). At such high column densities, the circumnuclear medium is Compton thick (CT). CT AGN are thought to account for the unresolved cosmic X-ray background (Churazov et al. 2007), producing 10−20% of the total 30 keV flux (Gilli et al. 2007; Treister et al. 2009). Identifying these sources and adding them to the comparison of the black hole accretion rate with the star formation rate history of the Universe is essential, as they are thought to be primarily missing at z<1 (Gilli et al. 2007; Treister et al. 2009), i.e., after the bulk of the stellar mass assembly (Marconi et al. 2004; Merloni et al. 2004; Gruppioni et al. 2011).

The sources missing from the cosmic X-ray background can be sought for in the cosmic background at infrared (IR) or longer wavelengths, as it is in these wavelengths that the radiation absorbed by the dust is re-emitted. Mid-IR excess (e.g., Lacy et al. 2004; Stern et al. 2005; Daddi et al. 2007; Fiore et al. 2008) and radio excess (Del Moro et al. 2012, in preparation) techniques have been used for this purpose. However, they do not preferentially select type 2 over type 1 AGN. We recently argued that in addition to an AGN tracer, a high column density indicator can be used to efficiently query for CT objects (Georgantopoulos et al. 2011). The latter was chosen to be the optical depth of the silicate feature at 9.7 μm, $\tau_{9.7}$, when seen in absorption. Even though the 9.7 μm and X-ray column densities are uncorrelated at moderate optical depths (Shi et al. 2006; Wu et al. 2009), the bulk of the silicates can still be in a compact, circum-nuclear distribution in front

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of a bright continuum source (Soifer et al. 2002; Tristram et al. 2007). They have even been suggested to be located in the AGN torus because their feature is often seen in emission in type-1 AGN and in absorption in type-2 AGN (Shi et al. 2006; Hao et al. 2007), in agreement with the Antonucci & Miller (1985) unification scheme. We specifically examined how frequently do the local AGN with the most extreme mid-IR obscuration, simply defined as those that are optically thick (τ>1) at 9.7 μm, have X-ray column densities $>10^{24}$ cm^{-2}. We then applied this criterion to query for CT candidates among distant AGN samples.

2 Sample selection

2.1 The 12 μm sample

To quantify the fraction of CT AGN that are identified using the $\tau_{9.7}$>1 criterion, we used all local 12 μm-selected Seyferts (Rush et al. 1993) with *Spitzer* IRS spectroscopy (Wu et al. 2009). Re-analysis of these spectra indicated that 11 out of the 103 Seyferts in this sample have $\tau_{9.7}$>1. Nine of those have X-ray spectra that are necessary to determine their X-ray column densities (e.g., Brightman & Nandra 2011; Georgantopoulos et al. 2011).

2.2 The GOODS and FLS samples

To identify AGN in the distant Universe that are deeply obscured in the mid-IR (Fig. 1; left panel), we used two surveys with *Spitzer* IRS spectroscopy and X-ray data. The Great Observatories Origins Deep Survey (GOODS) covering the *Chandra* Deep Fields (CDF) North and South, and the First Look Survey (FLS). The two surveys were complementary in providing targets. The FLS is a 4 deg^2 shallow survey, whose 220 IRS spectra were flux-limited to a depth of 0.9 mJy (mainly presented in Yan et al. 2007; Sajina et al. 2007; Dasyra et al. 2009). Its X-ray coverage was nonetheless sparse (Bauer et al. 2010). On the other hand, the GOODS area ($\sim$900 arcmin^2 in total) has the deepest mid-IR and X-ray observations available, but a sparse (not flux-limited) IRS spectroscopic coverage of 150 sources (Pope et al. 2012, in preparation).

Overall, 7 $\tau_{9.7}$>1 AGN with X-ray data were identified in GOODS North and South, and 5 in the FLS. The common criterion that we applied to classify distant sources as AGN was the lack of strong polycyclic aromatic hydrocarbon (PAH) emission, due either to the dilution of the PAHs into the AGN continuum or to the potential destruction of the PAHs by the AGN radiation. It translated to 6.2 (or 11.3) μm equivalent widths <0.3 μm. Several other direct AGN indicators were subsequently found in our sources, including the detection of narrow-line-region lines with widths >500 km s^{-1}, the unambiguous need for an AGN-heated dust component in the spectral energy distribution (SED) fitting (Fig. 1; right panel), and the X-ray luminosity L$_X$ values themselves, which exceeded $10^{42.5}$erg s^{-1} for many sources.

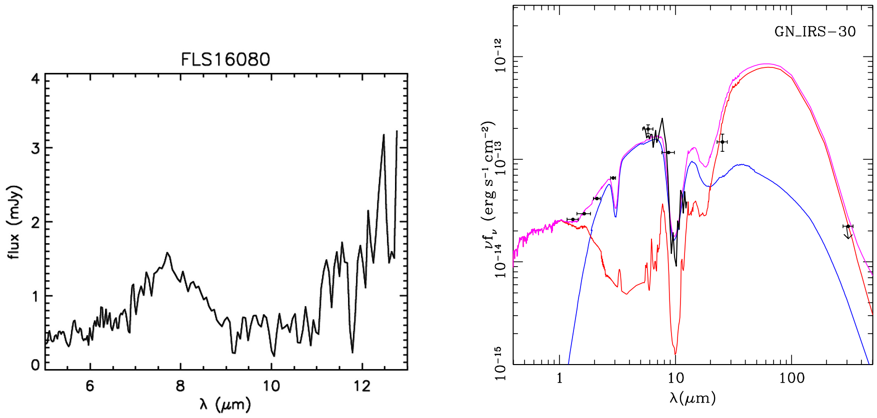

Fig. 1. Left: The mid-IR spectrum of a distant $\tau_{9.7}$>1 AGN in the FLS (Sajina et al. 2007). *Right*: SED decomposition of a GOODS $\tau_{9.7}$>1 source using an AGN (blue) and a starburst (red) component. The sum of the two is shown in magenta (Georgantopoulos et al. 2011).

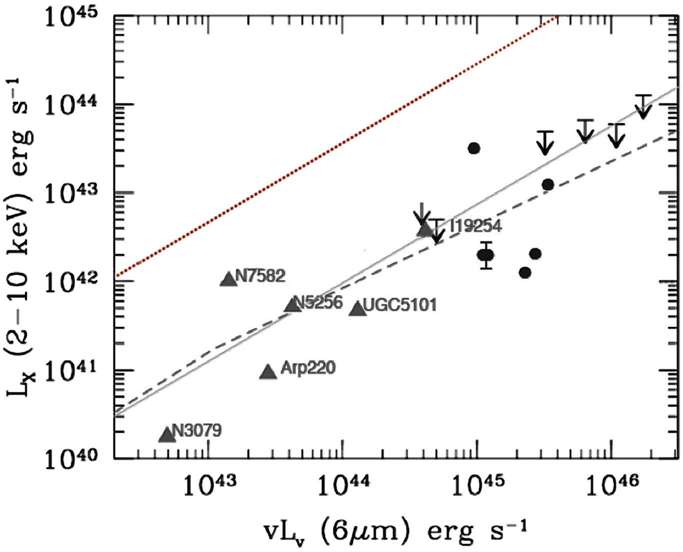

Fig. 2. Observed L_X vs $\nu L_\nu(6\,\mu m)$ diagram (adapted from Georgantopoulos et al. 2011). The solid and dashed lines indicate the area below which CT AGN lie, found for different AGN samples (Maiolino et al. 2007; Fiore et al. 2009, respectively) and for a fixed fraction, 0.03, of the intrinsic L_X value being ascribed to the 2-10 keV reflection component luminosity. For comparison, a relation with similar slope to that in Maiolino et al. (2007) that fits the intrinsic (extinction-corrected) X-ray and 6 μm luminosities of Seyfert 1 and 2 galaxies (Lutz et al. 2004) is shown with a dotted line. Local CT AGN with $\tau_{9.7}>1$ from the 12 μm sample are shown as triangles. Distant CT AGN candidates in GOODS and FLS are plotted with circles (or arrows for limits).

3 Results

Nine sources hosting a CT nucleus are known to exist in the sub-sample of 12 μm Seyferts with both IRS and X-ray spectra. These were identified through the detection of (i) a high (~ 1 keV) equivalent-width (EW) FeKα line, (ii) a flat X-ray spectrum (with index $\Gamma \sim 1$ or flatter), which is attributed to reflection from the back side of the torus, or (iii) an absorption turnover at high energies (Akylas & Georgantopoulos 2009). Six of the nine sources matching these criteria were found to also have $\tau_{9.7}>1$, suggesting that the identification of CT AGN using this $\tau_{9.7}$ threshold can be promising despite the different spatial distributions of the media responsible for the X-ray and IR obscuration.

The application of the same $\tau_{9.7}$ threshold for the GOODS and FLS samples enabled us to identify 12 CT AGN candidates at $0.8<z<2.7$. Because reliable X-ray spectra could not be derived for them, we used the observed L_X, integrated over the 2-10 keV range, vs $\nu L_\nu(6\,\mu m)$ diagram (Lutz et al. 2004) to assess which sources could be hosting a CT nucleus. With increasing obscuration, L_X drops and $L_\nu(6\,\mu m)$ increases, making the AGN move from the relation that is appropriate for the intrinsic (obscuration-corrected) luminosities (Fig. 2; dotted line) to the bottom-right part of the diagram. The boundary of the locus of CT AGN (solid line) is computed using the X-ray and 6 μm luminosities of the AGN presented in Maiolino et al. (2007). Given that this boundary depends on the SED and extinction properties of the objects in the chosen sample, we also computed it for the AGN in Fiore et al. (2009, shown with a dashed line, and additionally taking into account a luminosity evolution). We placed the 6 local $\tau_{9.7}>1$ CT AGN from the 12 μm sample on this diagram, and found that 5 of them are indeed below or close to either boundary. For the distant sources, we find that 4 of the 12 candidates are well within the CT range. Several more could be in it, given the proximity of their upper limits to the boundary. It is thus possible, that the fraction of actual CT AGN among these candidates is high. This remains to be confirmed with deep X-ray spectra.

Volume-density wise, our technique could provide a non-negligible fraction of the evasive AGN population. Of the 220 FLS IR-bright galaxies with IRS spectra, 20 satisfied both our $\tau_{9.7}$ and weak PAH emission criteria. The use of other, direct AGN tracers could make this fraction exceed 9%, as CT AGN can also be residing in strong starbursts (with $\tau_{9.7}>1$). In the combined GOODS North and South fields, the fraction of all 150 IR-bright galaxies with $\tau_{9.7}>1$ was 10% (15 sources), with 5% (7) of the sources having weak PAH emission

(Georgantopoulos et al. 2011). Potential $\tau_{9.7}>1$ (AGN or starburst) candidates in GOODS were found to correspond to 8−16% of the galaxies with only broad-band *Spitzer* and *Herschel* data (Magdis et al. 2011). Even in the local Universe, IR-bright galaxies are frequently optically thick at 9.7 μm (Imanishi 2009).

4 Conclusions

While not all CT sources have $\tau_{9.7}>1$ due to the clumpy structure of their obscuring medium, the efficiency of identifying them by querying for AGN that are optically thick at 9.7 μm can be high. Six of the nine Seyferts in the local 12 μm sample that are known to be CT from their X-ray spectral properties and that have *Spitzer* IRS spectra satisfied this criterion. In the GOODS and FLS surveys, we found twelve sources that are classified as AGN and that have $\tau_{9.7}>1$, four of which are likely to be CT according to their low X-ray to 6 μm luminosity ratio. While the number of sources presented in this work is limited due to the lack of either X-ray or IR data, the technique has the potential to provide large samples of CT AGN candidates.

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