THICK TORI AROUND ACTIVE GALACTIC NUCLEI: THE CASE FOR EXTENDED TORI AND CONSEQUENCES FOR THEIR X-RAY AND INFRARED EMISSION

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ABSTRACT

Two families of models of dusty tori in active galactic nuclei (AGNs; moderately thick and extended versus very thick and compact) are tested against available observations. The confrontation suggests that the former class better explains the infrared (IR) broadband spectra of both broad- and narrow-line AGNs, the anisotropy of the emission deduced by comparing IR properties of Seyfert 1 and 2 nuclei, and the results of IR spectroscopy and those of high spatial resolution observations. There is, however, clear evidence for a broad distribution of optical depths. We also examine the relationship between IR and X-ray emission. The data support a view in which the matter responsible for the X-ray absorption is mostly dust free, lying inside the dust sublimation radius. The consequences of these results for the hard X-ray background as well as IR counts and background are discussed.

Subject headings: dust, extinction — galaxies: active — galaxies: nuclei — galaxies: Seyfert — infrared: galaxies — radiative transfer

1. INTRODUCTION

Direct and indirect evidence of obscuring material around active galactic nuclei (AGNs) has been accumulated. High spatial resolution observations of emission from molecules and dust show that enriched gas is abundant around AGNs on scales ranging from a fraction of a parsec (see e.g., Miyoshi et al. 1995; Greenhill et al. 1995a, 1995b) to many tens of parsecs (see, e.g., Braatz et al. 1993; Jackson et al. 1993; Cameron et al. 1993; Tacconi et al. 1994; Genzel et al. 1995).

These results strongly support unified schemes of AGNs, according to which the distinction of AGNs in broad- and narrow-line objects is mainly due to orientation of circumnuclear dust structures. These schemes have been originally invoked to explain the results of spectropolarimetric observations, namely, that NGC 1068 (the prototype of Seyfert 2 galaxies) and several additional narrow-line AGNs show broad-line components in their spectra (see Antonucci 1993 for a comprehensive review). Direct view of the broad-line region (BLR) is blocked by an optically thick structure. The broad lines detected with spectropolarimetry are the result of the scattering into the line of sight of the radiation from the BLR by free electrons and/or dust particles above the nucleus. Moreover, in some optically narrow-line AGNs, broad lines have been detected with spectroscopy in the near-IR, where the absorption is less effective than in the optical bands (Rix et al. 1990; Ruiz, Rieke, & Schmidt 1994; Goodrich, Veilleux, & Hill 1994).

X-ray spectra of narrow-line AGNs exhibit absorption significantly larger than type 1 AGNs, providing strong support for the obscuring hypothesis (see, e.g., Nandra & Pounds 1994; Smith & Done 1996).

The anisotropy of the nuclear radiation (expected to be collimated in a cone with apex in the nucleus and opening angle determined by the absorbing structure) has been confirmed by images of emission lines of [O III], [N II], Hβ, and other elements for a significant number of narrow-line AGNs (see Wilson 1996 for a review), which show conical regions of high-excitation emission lines extending from the active nuclei.

More recently, the presence of obscuring tori also has been invoked to explain the difference between narrow- and broad-line radio galaxies (Barthel 1989). In this context the failed detection of CO J = 1–0 absorption from Cygnus A was embarrassing (Barvainis & Antonucci 1994). However, there are explanations that allow us to keep the presence of a dusty and molecular torus. In particular, Maloney, Begelman, & Rees (1994) showed that the nonthermal radio continuum may increase the excitation temperature of the lower rotational level, thus reducing the optical depth. Therefore, the lack of CO absorption may be a general property of the radio galaxies. Also, photodissociation, ionization, and heating by X-rays tend to decrease the CO absorption optical depth.

The energy absorbed by the obscuring structure must be reradiated in the IR. IR broadband spectra of nuclei of Seyfert galaxies can be fitted by models in which a significant fraction of the nuclear emission is reprocessed by an axisymmetric torus-like structure (Pier & Krolik 1992 [hereafter PK], 1993; Granato & Danese 1994, hereafter...
The absorbing structures around the active nuclei have usually been modeled as axial symmetric tori (PK; Pier & Krolik 1993; GD; Efstathiou & Rowan-Robinson 1994), although different geometries, such as warped disks, have also been suggested (Sanders et al. 1989). Models proposed by (PK; Pier & Krolik 1993) are characterized by extremely large optical thickness (\( \tau \gtrsim 1000 \)) in the UV, which entails \( \tau \gtrsim 10 \) at 10 \( \mu m \) and Thomson optical depth \( \tau_T \gtrsim 1 \) and compactness (radial dimension \( \lesssim a \) a few pc). Conversely, models proposed by GD are based on tori with optical depths in the UV band ranging from 10 to 300 and with maximum radii ranging from tens to hundreds of parsecs.

In § 2 the two families of models (moderately thick and extended vs. very thick and compact) are tested against observational information: IR broadband spectra (§ 2.1) and its anisotropy (§ 2.2), IR spectroscopy (§ 2.3), and high spatial resolution observations (§ 2.4). In § 3 we examine the links between IR and X-ray emission, and we show that the data support the view that the matter responsible for most of the X-ray absorption is dust free and lies inside the dust sublimation radius. The consequences of these results for the hard X-ray background (HXRB) as well as IR counts and background are then discussed in § 4, where we estimate in particular the dusty AGN counts in the IR bands relevant to the Infrared Space Observatory (ISO). The final section is devoted to summarizing our conclusions.

A Hubble constant \( H_0 = 50 \) km s \(^{-1}\) Mpc \(^{-1}\) and a deceleration parameter \( q_0 = -\frac{1}{2} \) have been assumed whenever necessary.

### 2. EXTENDED AND COMPACT TORI AND CONFRONTATION WITH THE DATA

As mentioned above, extended models have been investigated by GD and Efstathiou & Rowan-Robinson (1994), while compact and extremely thick models (\( \tau_T \gtrsim 1 \) and, correspondingly, \( A_V \gtrsim 800 \)) have been investigated by PK and Pier & Krolik 1993.

GD discussed a numerical code that solves the radiative transfer equation in a circumnuclear dust distribution. This step is required, since in the tori predicted by unified models the dust emission is self-absorbed, at least in the near- and mid-IR. The code is quite flexible concerning the geometry and composition of the dusty medium, the only restriction being axial symmetry, and thus allows a wide exploration of the parameter space, including both classes of models under discussion.

In the computations a standard galactic dust composition is assumed. The inner radius \( r_{in} \) of the dust distribution is set by the grain sublimation condition, above \( T_e = 1500 \) for graphite and \( T_e = 1000 \) for silicates. This translates into \( r_{in} \sim 0.5L_{45}^{1/2} \) pc, where \( L_{45} \) is the luminosity of the primary optical-UV emitter in units of \( 10^{45} \) ergs s \(^{-1}\).

The details of the model, as well as the effect of various free parameters, have been already discussed by GD. In this paper we wish to focus mainly on the radial extension of the dust distribution, measured by the ratio between the outer and inner radii \( r_{out}/r_{in} \), and on the absorption \( A_V \) along typical obscured directions. In Figure 1 we report representative spectral energy distributions (SEDs) predicted by our code for a broad range of \( A_V \) values. The average SED of the GD Seyfert 1 sample requires values for \( r_{out}/r_{in} \) of several hundreds and \( A_V \sim 30 \). Roughly speaking, the first parameter is related to the broadness of the IR bump arising from dust reprocessing, while the latter controls mainly the near-IR slope of the SEDs as observed from obscured directions as well as its anisotropy. Therefore, \( A_V \) is in principle constrained by the SEDs of obscured AGNs (§ 2.1) or by testing the anisotropy of mid-IR emission (§ 2.2).

#### 2.1. Infrared Broadband Spectra

In Figure 2 we present a good fit to the overall IR spectrum of NGC 1068, obtained with an extended and moderately thick torus characterized by an optical thickness smoothly dependent on the line of sight. In this model we used \( A_V \sim 72 \) along the line of sight, while the absorption is \( A_V \sim 220 \) in the equatorial plane. Assuming a distance \( D = 22 \) Mpc, the required primary optical-UV luminosity is \( \approx 1.5 \times 10^{45} \) ergs s \(^{-1}\), in nice agreement with the value obtained by UV spectropolarimetry with HST (Antonucci, Hurt, & Miller 1994). The total dust mass involved is \( 2.7 \times 10^4 M_\odot \), consistent with the estimates of gas masses (\( ~10^7 M_\odot \)) coming from CO observations. Although it is possible to obtain similar fits with different combinations of the free parameters and/or dust density laws, the extension and the optical depth, particularly along the line of sight, are reasonably well constrained to \( r_{out}/r_{in} \approx 100-200 \) and \( A_V \approx 50-100 \).

The information on IR nuclear spectra of Seyfert 2 galaxies other than NGC 1068 remains rather scanty. Attempts of evaluating near-IR nuclear fluxes are hampered by low fluxes of the nuclei with respect to the host galaxies. Moreover, data on the IR spectra of the nuclear regions have been collected through observations at various frequencies with significantly different spatial resolution. As a consequence, we must be cautious when referring to data collections as “nuclear SEDs.” Actually, only in a few cases of nearby Seyfert galaxies the data have angular resolution good enough to allow an estimate of the nuclear fluxes. Therefore, here we restrict ourselves to objects within a distance of 50 Mpc, where an angle of 2” subtends about 0.5 kpc.

Nine out of these galaxies have been observed within a small aperture both in the near-IR (\( \lesssim 4.5 \mu m \)) as well as at 10.6 \( \mu m \) (\( \lesssim 6 \)) and clearly detected. In Table 1 we report the ratio between the L and the N band emission for these narrow-line objects. In Figure 3 the same ratios, predicted by the GD models, are plotted as a function of the optical thickness \( A_V \) and for two values of \( r_{out}/r_{in} \). It is clear that the observed IR spectral slopes imply optical depths along the line of sight \( A_V \lesssim 80 \). Although the sample is not a fair one, and the data are likely to be affected by contributions from contaminating components, the result suggests that, at least for nearby objects, the optical depths are broadly distrib-
Fig. 1.—Examples of SEDs predicted by our radiative transfer code. In these cases the torus is homogeneous, it has a covering factor of 0.8, and \( r_{\text{out}} / r_{\text{in}} \) is set to 300. \( G \) Top to bottom, left to right: The adopted optical thickness along obscured directions are 30, 100, and 300. In each panel the solid line refers to a polar line of sight, while the dashed line is the SED observed from the equator.

### TABLE 1

| Name            | \( D \) (Mpc) | \( F(L) \) (mJy) | \( F(N) \) (mJy) | References | Ratio |
|-----------------|---------------|-----------------|-----------------|------------|-------|
| Circinus        | 3             | 701             | 6000            | 1, 2       | 0.35  |
| MCG - 5-23-16   | 48            | 79              | 530             | 4          | 0.44  |
| NGC 1068        | 22            | 1700            | 17800           | 3, 3       | 0.28  |
| NGC 1386        | 25            | 33              | 209             | 4, 5       | 0.47  |
| NGC 2110        | 45            | 47              | 198             | 6          | 0.71  |
| NGC 2992        | 45            | 74              | 259             | 6, 5       | 0.85  |
| NGC 4388        | 26            | 51              | 305             | 6          | 0.50  |
| NGC 5506        | 42            | 313             | 720             | 7          | 1.29  |
| NGC 7582        | 32            | 201             | 877             | 7, 1       | 0.68  |

Note.—Near- and mid-IR fluxes of nearby Seyfert 2 galaxies within small apertures. The photometric data are taken from various papers as follows: (1) Roche et al. 1991; (2) Maiolino et al. 1995; (3) Rieke & Low 1975; (4) Alonso-Herrero, Ward, & Kotilainen 1996; (5) Giuricin et al. 1995; (6) Mizutani, Suto, & Maihara 1994; (7) Kotilainen et al. 1992. The first reference number refers to L-band fluxes, the second one to N-band flux. The last column is the ratio between \( \nu F \), in the L band and N band.

A large spread of the optical depths, possibly associated with a dependence on the luminosity, has been invoked to reconcile the predictions of unified models to the observed statistics (Lawrence 1991). As noted by Granato, Danese, & Franceschini (1996), typical IR SEDs of high-luminosity ultraviolet excess QSOs are fitted by assuming reprocessing by dusty tori with equatorial optical thickness \( 3 \lesssim A_V \lesssim 10 \), while for Seyfert 1 galaxies the equatorial optical depths are found in the range \( 5 \lesssim A_V \lesssim 60 \). However, the equatorial optical depths of Type 1 objects are weakly constrained by the available IR and optical data.

This might suggest an anticorrelation of the typical optical depths and of the covering factors with luminosities,
This clearly breaks down the trend for a decreasing optical depth with increasing luminosity, but may well be linked to a transient phase when a young nucleus is wrapped in the gas of a young galaxy (Granato et al. 1996).

In summary, only a large range of optical depths can explain the observed IR spectra of narrow and broad-lined AGNs. There is no evidence in these data for circumnuclear tori with extremely large optical depths ($A_V \gtrsim 800$).

### 2.2. Anisotropy of Near- and Mid-Infrared Emission

Heckman (1995), Maiolino et al. (1995), and Giuricin, Mardirossian, & Mezzetti (1995) have examined the mid-IR emission of Seyfert 1 and 2 galaxies. Although the analyses were performed with different methods, a general consensus emerged that narrow-line (Seyfert 2) nuclei are weaker emitters than broad-line (Seyfert 1) nuclei. This may be interpreted as anisotropy resulting from the presence of the obscuring torus.

In particular, Heckman (1995) showed that the average ratio $S_{10}/S_{1.4}$ of 10.6 $\mu$m flux (within small aperture) to radio continuum at 1.4 GHz is about 4 times larger in Seyfert 1 than in type 2 Seyfert galaxies. Assuming that the radio emission is indicative of the nuclear power, he concluded that the putative torus is only mildly anisotropic. Since the data used by Heckman are rather heterogeneous, the basic assumption may be not completely safe. Actually, Giuricin, Fadda, & Mezzetti (1996) found that the total radio fluxes of Seyfert galaxies correlate with the radio core fluxes, but the total fluxes are about a factor of 6 larger. Moreover, the ratio may be influenced by a higher level of star formation in Seyfert 2 hosts (Maiolino et al. 1995), which entails an enhanced radio emission.

On the other hand Heckman (1995) also examined the ratio of 10.6 $\mu$m emission to the flux in the [O III] $\lambda 5007$ emission line. The average 10.6 $\mu$m emission, normalized to [O III] flux, of Seyfert 1 galaxies is larger than that of Seyfert 2 galaxies by a factor of 2. Although in this case the result may be affected by absorption and by possible bias in favor of small opening angles for Seyfert 2 galaxies, we can nevertheless conclude that the luminosity at 10 $\mu$m is higher by a factor ranging from 2 to 4 in Seyfert 1 galaxies, with respect to Seyfert 2 galaxies with the same nuclear luminosity.

The samples examined by Heckman (1995), namely, the RMS sample (Rush, Malkan, & Spinoglio 1993), the CfA sample (Huchra & Burg 1992), and a far-IR selected sample, all exhibit the same difference between Seyfert 1 and 2 galaxies.

For eight Seyfert 2 and nine Seyfert 1 galaxies of the RSA sample, which can be thought as a volume-limited sample, 10 $\mu$m fluxes taken within small aperture as well as radio and [O III] fluxes are available. Although this is a small subsample, the analysis nevertheless confirms that the 10 $\mu$m luminosity of the Seyfert 1 galaxies is only a factor of 2–4 higher than that of Seyfert 2 galaxies with the same nuclear luminosity.

As is apparent from Figure 4, the extended model predicts that Seyfert 1 galaxies are stronger emitters at 10 $\mu$m than Seyfert 2 galaxies by an average factor of 2–4, provided that the average absorption along the line of sight falls in the range $20 \lesssim A_V \lesssim 70$, in full agreement with the fits to available spectral data (see § 2.1 above). Also, Figure 4 shows that $A_V \gtrsim 150$ would imply an anisotropy 8–10 times larger than that observed in the analyzed samples. The angle $i$ between the torus axis and line of sight toward the...
nucleus is expected to be randomly distributed in the RSA sample and in the CfA sample, although in the latter some bias against very faint nuclei may be present, affecting the randomness of the inclination. For a random distribution, half of the nuclei should be seen with an inclination $i \gtrsim 60^\circ$, much larger than the average half-opening angle inferred from the ionization cones $\theta \lesssim 30^\circ$–$40^\circ$. Therefore, for a significant fraction of Seyfert 2 galaxies of the RSA and CfA samples the line of sight is expected to lie quite close to the equatorial plane of the torus and, as a consequence, to exhibit the largest absorption.

The GD torus model predicts that the anisotropy is rapidly decreasing with increasing wavelengths and, for the typical values of $A_V$ inferred from the above considerations, practically vanishes at around $30 \mu m$ (see Fig. 1). Indeed, Mulchaey et al. (1994) found that the distribution of the ratio of the integrated IR flux between 25 and $60 \mu m$ to the [O III] flux is rather similar for Seyfert 1 and 2 galaxies, with Seyfert 2 galaxies showing larger variance and a tail of higher IR to [O III] ratios, possibly because of starburst components (see §2.4).

In conclusion, the mild anisotropy estimated in various samples of Seyfert nuclei is well reproduced by the extended and moderately thick tori suggested by the fits to available broadband spectral data (§2.1). Conversely, in order to explain the observed anisotropy, the compact and very thick tori require a fine tuning of the fraction of inner torus walls directly seen by the observer, as well as additional emission of extended dust, possibly associated to the narrow-line region (NLR).

2.3. Infrared Spectroscopy of the Narrow-Line Nuclei

IR spectroscopy can potentially penetrate an obscuring torus and give direct evidence of the presence of a BLR completely obscured at optical wavelengths, where absorption is larger. Broad components of Paα and Paβ hydrogen lines have been searched for in active galaxies. Actually, the extinction at their near-IR wavelengths is a factor of 3–5 below that at Hz. Clear detection has been obtained for several narrow-line galaxies (Rix et al. 1990; Ruiz et al. 1994; Goodrich et al. 1994). The relevant result is that there are optically narrow-line active nuclei exhibiting broad lines when observed in the IR domain.

In three out 15 Seyfert 2 nuclei, selected with no particular criterion, Goodrich et al. (1994) were able to detect the broad component of the Paβ line, although their sensitivity limited possible detection to cases with $A_V \lesssim 11$. In the sample selected by Ruiz et al. (1994) on the basis of the relatively strong emission at $3 \mu m$ there are six out of nine nuclei with BLRs.

The detection of a broad component of the Paβ in the spectrum of the 1.9 Seyfert galaxy NGC 2992 suggests $A_V \sim 5$–8 (Goodrich et al. 1994; Rix et al. 1990). Similarly, in the case of NGC 5506 reddenings, values of $A_V \sim 5$–11 from IR broad lines have been reported (Goodrich et al. 1994; Rix et al. 1990). These reddenings agree reasonably well with those inferred from the IR colors of the nuclei (Table 1).

The existence of tori with modest optical depth is confirmed by observations of Paα lines in a complete sample of radio galaxies (Hill, Goodrich, & Depoy 1996). In three out of eight objects the broad component of the Paα has been clearly detected. The values of the reddening inferred from line ratios are in the range $2.7 \leq A_V \leq 7$.

On the other hand, larger reddenings of BLRs are surely present in narrow-line nuclei such as Cygnus A, exhibiting $A_V \gtrsim 24$ (Ward 1991), and NGC 1068.

These results are the most relevant in discriminating between extremely and mildly thick models, thanks to their rather different predictions. At the most basic level for extremely thick models, such as those presented by PK, the optical depth at near-IR, where BLRs have been detected, is so large ($f_{1.2} \gtrsim 100$) as to prevent detection of any IR broad line. In the case of extremely high optical depths the problem can be solved by assuming that the observed broad lines are scattered in the line of sight by a screen. In this hypothesis the lines are expected to be strongly polarized, while a low level of polarization is predicted for GD models. Thus, IR spectropolarimetry can discriminate between the two possibilities. In addition, in the case of the GD model we expect that narrow-line nuclei with significant emission at near-IR are objects seen along a less obscured line of sight and, as a consequence, with a more easily detectable BLR in the IR. Conversely, in the PK model there is no expected correlation between near IR flux (attributed to the visible portion of the inner walls) and the detectability of the BLR in the IR domain.

Thus, currently available IR spectroscopy data tend to exclude the general presence of tori optically very thick even at near IR as a rule, strengthening the findings of §§2.1 and 2.2.

2.4. High Spatial Resolution Observations and Obscuring Matter around Active Galactic Nuclei

Valuable information concerning the spatial extent of obscuring matter and, to a lesser extent, also its column densities, has come in the last few years from high spatial resolution observations, performed with different techniques.

On one hand, water maser line emission observed in the nucleus NGC 4258 at 22 GHz on a subparsec scale (Watson...
& Wallin 1994; Miyoshi et al. 1995; Greenhill et al. 1995a, 1995b) yields clear evidence of the presence of molecular gas very close to the active nucleus. On the other hand, the images obtained by the Planetary Camera of the *Hubble Space Telescope* (*HST*) of the active galaxy NGC 4261 clearly show an unresolved (<0.1 ≈ 7 pc) source surrounded by a dusty disk extending on a scale of 100 pc (Jaffe et al. 1993). This observation is a rather direct support to the idea of the existence of extended dusty tori around AGNs. Also, imaging in [O III] and Hα + [N II] lines with *HST* has revealed an unresolved region of very strong reddening within 23 pc of the nucleus of NGC 2110, a faint Seyfert 2 galaxy (Mulchaey et al. 1994).

H2 maps of the nuclear region of NGC 7469 present evidence of the presence of molecular gas in a Seyfert 1 galaxy (Genzel et al. 1995). With standard assumptions, a total gas mass of ≲ 108 M☉ is found to be within about 100 pc from the galaxy center. This amount is comparable to that found in a similar volume in NGC 1068 (Genzel et al. 1995).

High spatial resolution observations of molecular emission in NGC 1068 are available at various wavelengths (Planesas, Scoville, & Myers 1991; Jackson et al. 1993; Tacconi et al. 1994; Blietz et al. 1994). These observations show that the molecular gas extends over 100–200 pc far from the nucleus with a similar scale height. The associated total extinction may vary from A_V ≈ 10 up to 200.

In Figure 5 we present the maps at 2.2, 3.5, 10.5, and 25 μm of NGC 1068 predicted by the GD model. The size of the torus emission increases with increasing λ: the typical radius of the isophote at 10% of the peak runs from about 10 pc in the near-IR to more than 20 pc in the mid-IR. Bear in mind that the peak-normalized isophotes depend on the adopted point-spread function (PSF) anyway. The isophotes are elongated along directions with less absorption, in nice agreement with observations (Braatz et al. 1993; Cameron et al. 1993). However, our model extends over only 0.6, whereas these observations suggest significant emission up to 1.5–2″ at around 10 μm. Cameron et al. (1993) and Pier & Krolik (1993) envisaged the possibility that the extended mid-IR emission is due to dust located in the NLR. However, as pointed out by Cameron et al. (1993), this dust, if diffuse, would produce large absorption A_V ≈ 3–4, while measured values toward the NLR of NGC 1068 are A_V ≲ 1.5 (Inglis et al. 1995).

On the other hand, high angular resolution observations also showed that the star formation rate is significant in circumnuclear regions of a large majority of AGNs. Evidence of OB star associations in the very central regions (r ≲ 2″) of NGC 1068 has been found with COSTAR by Macchetto et al. (1994). Also, in NCG 7469 robust star formation is present (Genzel et al. 1995), as well as in Mrk 348 (Simpson et al. 1996). Thus, there might be a smooth transition of the mid- and far-IR emission from an inner

Fig. 5.—Brightness contours at four different wavelengths of the torus used to reproduce the SED of NGC 1068 and observed from θ = 65°. *Clockwise, from top left:* 25 μm, 10 μm, 2.2 μm, and 3.5 μm. The boxes have a width of 2r_out ≈ 0.6. The maps have been convolved with a Gaussian PSF with FWHM = 0.2r_out, and the levels refers to 0.01, 0.03, 0.1, 0.3, and 0.9 of the peak.
dusty torus with typical dimensions $r_{\text{out}} \sim 50 - 200 \, \text{pc}$, illuminated by the nucleus and responsible for most of the nuclear extinction, to a broader dusty region extending over several hundreds of parsecs, in which the dust is mainly heated by young stars.

The observations summarized in this section therefore confirm that the dense dusty medium is spread in the nuclear region from a fraction of a parsec up to hundreds of parsecs, yielding absorption $10 \lesssim A_V \lesssim 200$.

3. Relationship of the Torus with the X-Ray Absorption

Seyfert 1 galaxies often exhibit X-ray absorption in excess over the Galactic column density, although observed hydrogen column densities are usually $N_\text{H} \lesssim 10^{22} \, \text{cm}^{-2}$, with a median value $N_\text{H} \approx 10^{21}$ (Nandra & Pounds 1994). This agrees with the usual notion that in the case of broad-line AGNs the line of sight is relatively free of absorbing material. Conversely, hard X-ray spectra of Seyfert 2 galaxies show evidence of larger absorption, as expected in the unification scheme.

Spectra detailed enough to allow good estimates of the absorbing column density are available for 21 narrow-line active nuclei (see Smith & Done 1996; Iwasawa 1996). For this sample, admittedly not a complete one and presumably biased toward low values of the column density distribution ranges over $21.5 \leq \log N_\text{H} \leq 25$ with a median value $\log N_\text{H} \approx 23.3$, larger than that of Seyfert 1 galaxies by a factor of 200.

Although we assume that a fraction of objects with $N_\text{H} \gtrsim 10^{24}$ has been missed, these results nevertheless show that many of Seyfert 2 galaxies have tori optically thin to electron scattering (Thomson depth $\tau_T = 1$ corresponds to $N_\text{H} = 1.5 \times 10^{24}$ and $A_V = 750$).

Can the X-ray absorbing hydrogen column be associated to the dusty torus responsible for the UV and optical absorption and for the IR emission? Assuming standard dust over hydrogen abundance, the median log $N_\text{H} \approx 23.3$ translates into a median reddening $A_V \approx 100$. This would imply that the Seyfert 2 galaxies on the average should be fainter at 10 $\mu$m than Seyfert 1 galaxies by a factor of $\gtrsim 15$ (see Fig. 4), much larger than the factor 2–4 found by Heckman (1995). Indeed, in § 2.2 we have shown that this lower anisotropy of the torus emission, confirmed by our analysis of the RSA sample, requires $10 \lesssim A_V \lesssim 70$. The host galaxy cannot help much in accounting for this discrepancy, since the objects have been observed with small aperture (a few arcseconds). Defining $A_V^\text{IR}$ as the absorption in the $V$ band that is associated to the X-ray absorbing column density $N_\text{H}$ under the assumption of a normal gas-to-dust ratio, and $A_V^\text{IR}$ the absorption derived from the IR spectra, we may infer that on the average, $A_V^\text{IR} \approx 0.1 - 0.5 A_V^\text{X}$.

The discrepancy is confirmed by the analysis of a sample of objects with accurately determined X-ray spectra, [O III] line fluxes, and 10 $\mu$m fluxes. The relevant data are reported in Table 2. The 12 Seyfert 1 galaxies of the sample show a rather narrow distribution of the ratios of the X-ray to

| Name                | $N_\text{H}$ | $F_{2-10}$ | $F_{5007}$ | $F_{10\mu\text{m}}$ | Reference (X-Ray) | Reference (IR) | $X$-Ray/IR | X-Ray/O III | IR/O III |
|---------------------|-------------|-----------|------------|---------------------|-------------------|----------------|------------|-------------|----------|
| IC 4329             | 12.3        | 34        | 22.0       | 1                   | 2                 | 0.56           | 362        | 647         |
| MGC -6-30-15        | 5.6         | 82        | 3          | 2                   | 2                 | 0.68           | ...        | ...         |
| Mrk 1040            | 2.6         | 13        | 9.4        | 3                   | 2                 | 0.28           | 200        | 723         |
| Mrk 335             | 1.3         | 23        | 6.0        | 1                   | 2                 | 0.21           | 54         | 260         |
| Mrk 509             | 5.0         | 81        | 6.8        | 1                   | 3                 | 0.74           | 62         | 84          |
| Mrk 79              | 2.5         | 37        | 7.2        | 3                   | 2                 | 0.35           | 68         | 195         |
| NGC 1365            | 2.6         | 10.0      | 3          | 2                   | 0.26              | ...            | ...        | ...         |
| NGC 3227            | 4.0         | 64        | 7.9        | 1                   | 2                 | 0.51           | 63         | 123         |
| NGC 3516            | 2.1         | 48        | 6.4        | 1                   | 2                 | 0.33           | 43         | 133         |
| NGC 3783            | 7.2         | 130       | 14.0       | 3                   | 2                 | 0.51           | 55         | 108         |
| NGC 4051            | 1.9         | 39        | 9.0        | 1                   | 2                 | 0.21           | 49         | 231         |
| NGC 4593            | 3.7         | 17        | 5.0        | 3                   | 3                 | 0.74           | 218        | 294         |
| NGC 5548            | 3.2         | 58        | 4.6        | 1                   | 2                 | 0.70           | 55         | 79          |
| NGC 7213            | 3.8         | 7.5       | 1          | 2                   | 0.51              | ...            | ...        | ...         |
| NGC 7469            | 3.7         | 58        | 23.0       | 1                   | 2                 | 0.16           | 64         | 397         |

**Table 2**

**X-Ray Data for Seyfert Nuclei**

| Name                | $N_\text{H}$ | $F_{2-10}$ | $F_{5007}$ | $F_{10\mu\text{m}}$ | Reference (X-Ray) | Reference (IR) | $X$-Ray/IR | X-Ray/O III | IR/O III |
|---------------------|-------------|-----------|------------|---------------------|-------------------|----------------|------------|-------------|----------|
| IC 5063             | 370         | 1.0       | 93         | ...                | 4                 | ...            | 11         | ...         |...        |
| MCG -5-23-16        | 20          | 3.0       | 23         | 15.0               | 4                 | 6              | 0.20       | 131         | 652      |
| Mrk 3               | 810         | 1.0       | 347        | 8.1                | 4                 | 2              | 0.13       | 3           | 23       |
| Mrk 348             | 133         | 1.3       | 42         | 8.6                | 4                 | 2              | 0.15       | 30          | 205      |
| NGC 2110            | 25          | 3.5       | 17         | 5.6                | 4                 | 6              | 0.62       | 204         | 329      |
| NGC 2992            | 19          | 1.6       | 91         | 7.3                | 4                 | 2              | 0.22       | 18          | 80       |
| NGC 4388            | 380         | 1.4       | 48         | 8.6                | 5                 | 6              | 0.16       | 29          | 179      |
| NGC 4507            | 593         | 1.6       | 110        | 6.5                | 4                 | 2              | 0.25       | 15          | 59       |
| NGC 526A            | 23          | 1.0       | 27         | 4.8                | 4                 | 6              | 0.72       | 122         | 453      |
| NGC 5506            | 39          | 5.5       | 45         | 20.4               | 4                 | 6              | 0.27       | 122         | 453      |
| NGC 7314            | 6           | 2.9       | 6.1        | ...                | 4                 | ...            | 477        | ...         |...        |

**Notes:** X-ray data for Seyfert nuclei with well-determined X-ray spectra. $N_\text{H}$ is given in $10^{21} \, \text{cm}^{-2}$. $F_{2-10}$, $F_{5007}$, and $F_{10\mu\text{m}}$ are the 2–10 keV, the [O III] 25007 and the N-band fluxes in units of $10^{-12}$, $10^{-14}$, and $10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, respectively. Reference codes for IR data are (2) Giuricin et al. 1995; (6) Roche et al. 1991. The [O III] fluxes are taken from Whittle 1992. References for X-ray data are (1) Nandra & Pounds 1994; (3) Malaguti, Bassani, & Caroli 1994; (4) Smith & Done 1996; (5) Iwasawa 1996.
[O III] flux, 40 \leq F_{2-10}/F_{5007} \leq 360 \ (\text{fluxes expressed in epgs s}^{-1} \text{cm}^{-2})\), smaller values being associated with higher column densities. For the same objects the spread of the distribution of $F_{10 \mu m}/F_{5007}$ is limited to a factor of 9, which is smaller than the factor of about 40 found by Heckman (1995). The effect is attributable to the fact that the contamination by underlying galaxy is lower in our sample, since the objects are relatively nearby. These results confirm that the normalization to the intrinsic nuclear luminosity through the [O III] emission is appropriate, though absorption and use of different apertures in the observations clearly introduce noise.

The median value for the 12 Seyfert 1 galaxies is $F_{2-10}/F_{5007} \approx 60$, larger than that of the 11 Seyfert 2 galaxies by a factor 2. With a numerical code that solves the transport equation for X-rays, taking into account both photoelectric absorption as well as Compton scattering (Granato 1997), we found that a decrease of a factor of 2 implies an average column density $N_H \approx 1 \times 10^{23}$ for the obscured objects, only a factor of 2 smaller than the median column density found in the Seyfert 2 galaxy sample.

If the material responsible for the X-ray absorption had a normal gas-to-dust ratio, then we would expect $N_H \approx 50$ and a ratio of IR to [O III] fluxes that is at least a factor of 4 smaller for narrow-line active galaxies, while the ratio of the IR to [O III] fluxes is rather similar for the broad- and narrow-line galaxies of the sample.

Good correlation exists between the ratio of 2–10 keV flux $F_{2-10}$ to the O [III] line flux $F_{5007}$ and the X-ray absorbing column density of the Seyfert 2 sample (see Fig. 6). A similar level of correlation is also present between the column density and the ratio of the 10 \mu m fluxes $F_{10 \mu m}$ to $F_{5007}$ for the eight objects for which IR measurements are available. This result is understood if we assume some degree of correlation between the X-ray absorbing column density and the optical depth due to the dust.

The 15 Seyfert 1 galaxies of the sample in Table 2 exhibit ratios $0.16 \leq F_{2-10}/F_{10 \mu m} \leq 0.7$ with a median value 0.5, while for the eight Seyfert 2 galaxies the ratios are significantly clustered around 0.2. Hence the Seyfert 1 galaxies have an X-ray to mid-IR average ratio larger by a factor of about 2 than that of Seyfert 2 galaxies. On the other hand, in any reasonable model in which $A_V^\text{IR}$ is forced to be equal to $A_V^\text{X}$ the ratio

$$R = \frac{(F_{2-10}/F_{10 \mu m})_{\text{Sy1}}}{(F_{2-10}/F_{10 \mu m})_{\text{Sy2}}} = \frac{F_{10 \mu m,\text{Sy2}}}{F_{2-10,\text{Sy2}}}/(F_{10 \mu m,\text{Sy1}}/F_{2-10,\text{Sy1}})$$

turns out to be well below 1 (Fig. 7). In particular with $A_V^\text{IR} = A_V^\text{X} \approx 100$ (the median $A_V^\text{X}$ value), our radiative transfer codes predict $R \approx 0.05$. Once more, the discrepancy is solved if $A_V^\text{IR} \sim 0.14 A_V^\text{X}$.

The link of the X-ray to the mid-IR emission in AGNs has been investigated also by Barcons et al. (1995), who measured the X-ray intensities in the nominal band 2–10 keV, as observed by the experiment A2 on board the HEAO 1 satellite, at the positions of the RMS sample of AGNs selected at 12 \mu m by IRAS. After subtracting the “blank sky,” they found that the ratio of the flux at 5 keV to the flux at 12 \mu m $f_{5007}/f_{12} = 1.4^{+0.4}_{-0.3} \times 10^{-6}$ for the 54 Seyfert 1 galaxies and $f_{5007}/f_{12} = 2.0^{+0.5}_{-0.3} \times 10^{-7}$ for 59 Seyfert 2 galaxies a factor of 7 lower. The low angular resolution of the IRAS data implies that the host galaxies contribute to the 12 \mu m fluxes, in a way depending on the relative strength of the galaxy to the nucleus as well as on distance. Maiolino et al. (1995) claim that the typical host galaxy of a Seyfert 2 nucleus is 5 times more luminous that the typical Seyfert 1 host galaxy. Thus, part of the factor of 7 found by Barcons et al. (1995) as the difference in the X-ray to IR ratio may be accounted for by this effect. However, also for this IR selected sample the ratio of the X-ray to the mid-IR emission is larger for type 1 Seyfert galaxies, while, assuming $A_V^\text{X} = A_V^\text{IR}$, the opposite is expected.

It is worth noticing that the median value $F_{2-10}/F_{10 \mu m} \approx 0.5$ found for the Seyfert 1 galaxies of Table 2 translates into $f_{5007}/f_{12} \approx 6 \times 10^{-6}$, a factor of about 4 larger than the value given by Barcons et al. (1995). On the other hand, the sample of Table 2 can be thought as X-ray selected and thus is biased toward larger X-ray to IR ratios.

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**Fig. 6.—Correlation between the $N_H$ derived from X-ray spectral fits and the X-ray and IR luminosities normalized to the O III luminosity.**

**Fig. 7.—**$R$ is the ratio $(f_{5007}/f_{12})_{\text{Sy1}}/(f_{5007}/f_{12})_{\text{Sy2}}$ predicted by our radiative transfer codes for IR and X-ray, when $A_V^\text{IR}$ is forced to be equal to $A_V^\text{X}$. Observationally, $R > 1$, while for $A_V^\text{X} \approx 100$, the mean observed value $R$ should be about 0.05. To solve the discrepancy, $A_V^\text{IR} \sim 0.24 A_V^\text{X}$ is required.
If the parent population has a dispersion $\sigma \sim 0.4$ in the distribution of the logarithms of the IR to X-ray luminosity ratios, then the factor 4 is easily recovered (see eq. [14] of Barcons et al. 1995).

For a handful of objects the absorption in the visual band $A_V^c$, calculated under the assumption that the X-ray absorbing gas has a normal gas-to-dust ratio, can be directly compared to that derived from the IR spectrum $A_V^r$ and/or to the absorption derived from IR broad lines $A_V^{BL}$. NGC 2992 has low $A_V^c \simeq 11$, and $A_V^r$ is not well determined but possibly small, $\simeq 5-11$. It is worth mentioning that Weaver et al. (1996) proposed that the Fe Kα fluorescence line in this source is reprocessed at distance of 10 ± 4 lt-yr from the central source in a region with $N_H \simeq (2-4) \times 10^{23}$. The argument is based on long-term variability of the line equivalent width of a factor 3, compared to a continuum variation of a factor 20. However, the poor time statistic does not exclude a significantly smaller distance of the reprocessing material. Similarly, in NGC 5506 $A_V^c \simeq 19$, the IR broad spectrum demands low absorption, and $A_V^{IR} \simeq 5-11$. A significant change in the relationship between X-ray and IR absorptions is apparent at higher X-ray column density. Indeed, NGC 4388 $A_V^c \simeq 190$, while $A_V^{IR} \simeq 5$ and IR broad lines have not been detected. The IR spectrum of Mrk 348 suggests $A_V^r \simeq 7-10$ (Roche et al. 1991) and indeed the broad component of He I (1.083 μm) line has been detected (Ruiz et al. 1994).

For the same object Smith & Done (1996) estimated $N_H \simeq 1.3 \times 10^{23}$, corresponding to $A_V^c \simeq 70$. In NGC 1068 the GD model of the IR spectrum requires $A_V^{IR} \simeq 72$ along the line of sight, while X-ray spectral observations suggest $A_V^c \geq 4000$, almost 500 times larger. Similar conclusions holds for Circinus: the beautiful spectrum obtained with the SWS on board ISO by Moorwood et al. (1996) demands $A_V^{IR} \sim 50$, while the X-ray spectrum obtained by Matt et al. (1996) with ASCA implies $N_H \gtrsim 10^{24}$ at least and thus $A_V^c \gtrsim 500$.

Therefore, for the objects of Table 2 for which reliable determinations of X-ray and IR absorption are available, we find $A_V^{IR} \sim 0.002-1A_V^c$, the equality holding only for objects with low $N_H$.

This behavior is confirmed by high-luminosity objects, which can be identified with type 2 QSOs. The IR and optical spectrum of IRAS 09104 is nicely fitted by a GD torus with an absorption along the line of sight $A_V^{IR} \simeq 11$ (Granato et al. 1996), while the X-ray spectrum indicates that only scattered radiation is seen with ASCA (Fabian & Crawford 1995), implying $N_H \gg 1.5 \times 10^{24}$ and, as a consequence, $A_V^c \gtrsim 800$. For IRAS 10214 the line of sight absorption is $A_V^{IR} \sim 150$, while X-ray upper limits suggest $A_V^c \gtrsim 1500$ (Granato et al. 1996).

In conclusion, the available data, combined with the GD model, imply that $A_V^{IR} \sim A_V^c$ at low X-ray column density $N_H \lessgtr \text{few} \times 10^{22}$, while when $3 \times 10^{22} \lesssim N_H \lesssim 10^{24}$, we have $A_V^{IR} \sim 0.1A_V^c$. Finally, $A_V^{IR} \ll 0.1A_V^c$ for the largest measured column densities $N_H \gtrsim 10^{24}$.

### 3.1. Interpretations

Although the overall picture may be quite complex, and data may be plagued by systematic effects such as X-ray variability, there nevertheless is evidence that the gas responsible for the X-ray absorption is, in general, dust free and that the dusty torus in Seyfert 2 galaxies is not the site wherein the bulk of the X-ray absorption occurs. Only in the least absorbed objects do we find that $A_V^{IR} \sim A_V^c$. Moreover, in the data there is no significant trend of the ratio of the X-ray to IR absorption in type 2 AGNs on the luminosity. The increasing number of claimed detections of type 2 QSOs (see, e.g., Boyle et al. 1995; Almaini et al. 1995; Ohta et al. 1996) is suggestive of a weak, if not null, correlation of the absorptions themselves with luminosity.

The most natural explanation of these results is that the X-ray absorption occurs in gas that lies inside the dust sublimation radius. The nuclear activity implies a reservoir of interstellar medium (ISM), which, flowing toward the nucleus, fuels the central black hole (BH). We identify the reservoir with the dusty extended torus, and we relate the X-ray absorbing structure with the material that, on the way from the reservoir to the accretion disk, is already beyond the dust sublimation radius. Assuming that inside this radius the gravity is dominated by the central BH and that a quasi steady state is established, we can derive the expected density by mass conservation

$$\rho = \frac{M}{4\pi r^2 v_f},$$

where $M$ is the accretion rate and $v_f$ is the radial drift velocity. If we introduce the ratio of the drift to the circular velocity $k = v_f/v_g \sim 0.01-0.1$ (see, e.g., Blackman & Yi 1996; Krolik & Begelman 1988) and we assume that the circular velocity is nearly Keplerian, then we get for the hydrogen number density

$$n_H \simeq \frac{1}{4\pi km_v G^{1/2} f^{3/2} N_{BL}^{1/2}}.$$

The sublimation radius is $r_{in} \simeq 0.5L_{46}^{1/2} \text{pc}$, about a factor of 2–3 larger than the BLR typical radius. In the intermediate region dust is disrupted, but the metal-rich gas absorbs the X-ray flux coming from the nucleus. Let this region extend from $r_{in}$ to $r_{in}$ and $F = L/L_{Edd}$. Then the expected column density of this region is

$$N_H \simeq \frac{0.8 \times 10^{23}}{k} \left( f^{-1/2} - 1 \right) \epsilon_{0.1}^{1/2} F^{1/2} L_{46}^{1/2} \text{cm}^{-2},$$

where $\epsilon_{0.1}$ is the efficiency of mass into radiation conversion normalized to 0.1, and the radial integration assumes a constant $k$. Inserting the reasonable values $f \sim 0.5$ and $\epsilon_{0.1} \sim 1$, we get for Seyfert nuclei with luminosity in the range $10^{44}-10^{45}$ and emitting near the Eddington limit $10^{25} \lesssim N_H \lesssim 10^{24}$ for $k \sim 0.01-0.1$. Although this view is admittedly crude, we expect that at about the sublimation radius radiation pressure, differential rotation, viscosity and gravitational field are arranged in a way to allow gas feeding the central BH (see, e.g., Krolik & Begelman 1988; Yi, Field, & Blackman 1994; Blackman & Yi 1996; Granato et al. 1997).

Interestingly enough, the dependence on the total luminosity is relatively weak, while it is more pronounced that on $F = L/L_{Edd}$. The column densities observed in Seyfert 2 galaxies suggest that they are emitting at the Eddington limit.

In conclusion, from the analysis of available IR and X-ray data, it is apparent that the X-ray absorption in type 2 AGNs is chiefly due to matter free from dust, located at and just inside the dust sublimation radius and flowing toward the accretion disk.
4. ACTIVE GALACTIC NUCLEUS STATISTICS AND THE X-RAY AND IR BACKGROUND

The relative fraction of broad-lined and narrow-lined AGNs is extremely relevant to a number of problems, such as the validity of the unified schemes (see Lawrence 1991), the origin of the XRB (see, e.g., Setti & Woltjer 1989) and the contribution of the AGNs to the IR background (Granato, Franceschini, & Danese 1995). Unfortunately, the available statistics mainly refer to the local populations, while for the X-ray and IR backgrounds the relevant statistics concern objects at substantial redshift $z \gtrsim 1$. On the other hand, we may derive interesting clues also from local samples.

Lawrence (1991) showed that the fraction of local narrow-line AGNs may range from 0.7 to 0.84 in optically selected samples, after corrections for bias. Of course the statistics is rather poor for faint objects, even in the case of local samples. To overcome this bias Maiolino & Rieke (1995) examined the RSA sample and found that the fraction of type 2 nuclei may be as large as 0.8, with an important fraction of low-luminosity objects.

Assuming that the relative number of AGNs merely reflects the average opening angle $\Theta_H$ of the dusty torus, the optical samples suggest $35^\circ \lesssim \Theta_H \lesssim 45^\circ$, a range confirmed also by the observations of ionization cones.

The large RMS sample of 116 Seyfert galaxies selected at 12 $\mu$m exhibits an almost identical fraction of type 1 and type 2 objects. To understand this result, we have to take into account that, on the average, type 1 objects are brighter by a factor of 2–4 (Heckman 1995) and that the host galaxy contribution is not negligible for the objects in the RMS sample, because of the poor angular resolution of IRAS. Indeed, under the assumptions that locally the host galaxy is as luminous as the active nucleus in type 1 objects at 12 $\mu$m and 3 times more luminous in type 2 objects, and that type 2 objects are 4 times more numerous than type 1, we predict almost the same number of the two types at the IRAS 12 $\mu$m survey flux limit.

The statistics on the X-ray absorption is still rather poor. The $N_H$ distribution of the Seyfert 2 galaxies detected in hard X-ray bands (Smith & Done 1996) shows that a significant fraction of about 40% of the objects has $N_H < 10^{23}$ and only 15% has $N_H > 10^{24}$. This result must be taken with caution, as it is surely plagued by bias against highly absorbed objects. However, following the conclusions of the previous section, surveys in the mid-IR bands will not miss many of the highly X-ray absorbed AGNs and will be extremely helpful in settling down the relative fraction of type 1 and 2 objects.

This fact is extremely relevant to the problem of the XRB. As proposed by Setti & Woltjer (1989), the HXRB from 3 to 100 keV can be fitted by the integrated emission of heavily absorbed AGNs (see also Zdziarski, Zycki, & Krolik 1993; Madau et al. 1993; Comastri et al. 1995; Celotti et al. 1995). Although with some differences, all these authors concluded that the HXRB can be produced by an evolving population of obscured AGNs, characterized by local luminosity function and local volume emissivity within the observational boundaries and endowed with a significant cosmological evolution up to $z_{\text{max}} \sim 2.5–5$ \cite{Celotti1995} ($\langle nL \rangle \propto (1+z)^C$, with $C = 2.2–2.7$). The obscured AGNs are required to be 2–4 times more numerous than the unobscured ones. About 50% of the obscured AGNs are required to have $N_H > 10^{23}$ and about 35% to have $1 \times 10^{24} \lesssim N_H \lesssim 5 \times 10^{24}$ (see, e.g., Celotti et al. 1995). These requirements are consistent with the limits imposed by observations, although not by as wide a margin as for the column density distribution (see Smith & Done 1996).

A viable alternative solution for the HXRB has been worked out by Franceschini et al. (1993), who proposed, on the basis of the available X-ray source counts and related statistics, that the HXRB is mainly contributed by a population of AGNs endowed with luminosity and spectral evolution (luminosity and column density increasing with increasing redshift). Although both schemes imply that a significant number of absorbed AGNs contributing to the HXRB will be detected with the ISO surveys, the different assumption about spectral evolution nevertheless will be mirrored in the IR surveys with a different redshift distribution of the type 2 AGNs.

In Figure 8 and in Table 3 we present the AGNs counts at 15 $\mu$m and 6.7 $\mu$m, the two effective wavelengths of the surveys of the mid-infrared camera on the ISO computed with the prescription that they produce the HXRB. In order to work out IR count predictions, the ratio of the 2–10 keV luminosity $L_{2-10}$ to the luminosity in the 10 $\mu$m band $L_{10\mu m}$ of the unabsorbed objects must be specified. The 12 type 1 objects reported in Table 2 show an average value of 0.5 of this ratio. A similar value $\approx 0.4$ may also be inferred by SED of the UVSX QSO sample reported by Elvis et al. (1994). We used the results of § 3 to infer the dust absorption in the torus at given hydrogen column density. In the total flux a contribution from a nonevolving host galaxy is also included, as described above.

From Table 3 it is apparent that the ISO mid-infrared surveys will be extremely efficient in detecting the dusty AGNs. They will provide very sound statistics allowing to understand both the relative number of type 1 and 2 in the local universe as well as their respective evolution.

Using the IR counts, we can compute the contribution to

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{AGN counts predicted in mid-IR bands under the requirement that they produce the hard X-ray background. The dashed line and the dotted line refer to obscured and unobscured nuclei, respectively.}
\end{figure}
the IR background of the objects producing the HXRB, which turns out to be rather flat from several microns to 200 \(\mu m\) at a level of \(\approx 2 \times 10^{-10} W m^{-2} sr^{-1}\) (Fig. 9). This is only a lower limit to the AGN contribution, since it is based only on hard X-ray emitting objects. It is worth noticing that this corresponds to about 5 times the local energy density of the XRB \(\approx 8 \times 10^{-17} ergs cm^{-3}\) from 1 keV to MeV and still is only a fraction of the IR background produced by normal galaxies (see, e.g., Franceschini et al. 1995).

The request of modeling the HXRB spectrum summing up absorbed sources implies that only a small fraction of the total energy is stored in the HXRB. To illustrate the problem we can compute the BH mass density required to supply the XRB. This is rather easily done for the model proposed by Celotti et al. (1995), who proposed that absorbed AGNs share the same 2–10 keV luminosity function and the same luminosity evolution of the unabsorbed ones but are a factor around 2.5 more numerous. Using the 47 SEDs of the UV soft X-ray sample of QSOs (Elvis et al. 1994), the average bolometric correction of the 2–10 keV band is \(k_{bol} \approx 38\) with very small dispersion. Since the sample includes 29 radio-quiet and 18 radio-loud objects, the value found possibly underestimates the bolometric correction for radio-quiet objects. Finally, the mass density of the BHs associated to the XRB is

\[\rho_{BH} \approx 4 \times 10^5 \epsilon_{0.1}^{-1} k_{bol} M_\odot Mpc^{-3},\]

where \(\epsilon_{0.1}\) is the mass-to-energy conversion efficiency normalized to 0.1. This value has to be compared to \(\rho_{BH} \approx 1.4 \times 10^5 \epsilon_{0.1}^{-1} M_\odot Mpc^{-3}\) found by Chokshi & Turner (1992) for the optical selected AGNs. By using the galaxy local luminosity function by Efstathiou et al. (1988), we find that the production of the XRB implies that almost all the galaxies with \(M_B < -17\) should harbor a BH with \(M \geq 4 \times 10^7 M_\odot\). The consequences and implications will be examined elsewhere.

5. SUMMARY AND CONCLUSIONS

The statistics of large samples of AGNs (CfA, RSA, RMS, and others) on the differences of 10 \(\mu m\) nuclear emission between broad- and narrow-line AGNs show that the anisotropy amounts to a factor of 2–4, implying that the narrow-line objects of these samples have, on average, dust absorption in the range 10 \(\lesssim A_V \lesssim 80\). The detection of broad components of IR permitted lines such as Pas in a number of narrow-line active nuclei confirms that low optical depths are not an exception. Available data on IR spectra of AGNs strongly support the same conclusion, adding evidence for a significant spread of \(A_V\) in narrow-line objects.

Since we would also expect in the CfA and RSA samples objects seen along lines of sight close to the equatorial plane, these results imply that the absorption due to dust in the torus is actually significantly smaller than predicted by PK torus models with \(\tau_T \approx 1\) and \(A_V \sim 800\). GD extended torus models are naturally in agreement with these results. For instance, the fit to the NGC 1068 nuclear IR spectrum is obtained with \(A_V \approx 72\) along the line of sight. Moreover, the predicted maps of the mid-IR emission are extended and thus in good agreement with the observation, though additional emission from the regions just outside the torus seems to be requested. This additional emission has been already observed in several cases and attributed to the star formation activity, which is quite natural in these astrophysical settings.

Interestingly enough, the IR broadband spectra of broad-line AGNs also can be fitted by models with dust absorption in the equatorial plane confined at 5 \(\lesssim A_V \lesssim 50\). The largest values of dust absorption \(A_V \approx 200\) are required when fitting high-redshift and high-luminosity narrow-line objects (but also broad-line ones such as the Cloverleaf quasar). These active nuclei plausibly are in a phase of high activity and have a large reservoir of mass available to the accretion, which is also responsible for a large covering of the nuclear region. These cases look rather extreme, but

![Fig. 9.—Contribution of AGNs to the IR background (heavy line), compared with the predicted emission of galaxies (Franceschini et al. 1994), the tentative submillimeter detection by Puget et al. (1996) (shaded region), and available limits by Hauser (1994).](image-url)
notwithstanding that they exhibit dust absorption significantly less than that implied by models with \( A_V > 800 \).

The emerging picture suggests that the strictly unified scheme does not hold. There is evidence for large spread in optical depth distribution in both type 1 and type 2 nuclei. Also, the average covering factor may change from obscured to unobscured AGNs. Dependence of these parameters on luminosity is not evident, while there are cases of objects with quite different luminosities exhibiting high absorption and high covering factors. We suggest that these parameters depend more on the conditions of the interstellar medium of the host galaxy than on the nuclear luminosity.

Since the IR observations can be fitted by GD torus models predicting a relatively low \( A_V \) for the dust, the next question was about the origin of the X-ray absorption in narrow-line AGNs. The data show a rather strict relationship among the column density of the X-ray absorbing material and the dust absorption in the torus, for several cases in which we can observationally infer both of them. However, we found that \( A^\text{IR}_V \sim A^\text{H}_V \) only for low hydrogen column densities \( N_H \lesssim 10^{20} \), while for \( 3 \times 10^{22} \lesssim N_H \lesssim 10^{24} \), \( A^\text{IR}_V \sim 0.1 A^\text{H}_V \), and for \( N_H \gtrsim 10^{24} \), \( A^\text{IR}_V \sim 0.1 A^\text{H}_V \).

We propose that the X-ray absorption takes place mainly in the region just inside the dust sublimation radius, where dust is disrupted but a metal enriched gas exists. In this scheme the dusty torus reflects more the conditions of the reservoir of the material available for the accretion, while the X-ray absorbing column density reflects the conditions in a region that is dominated by the BH physics. Indeed, we showed that the X-ray column density can be related to the ratio \( L/\dot{E}_{\text{edd}} \) at which the nucleus is radiating, with higher \( L/\dot{E}_{\text{edd}} \) implying higher column density.

The conclusion that the dusty tori are not thick enough to absorb the mid-IR nuclear radiation implies that mid-IR surveys should be able to detect a large number of narrow-line AGNs, particularly those with \( N_H \lesssim 2 \times 10^{24} \), which are supposed to be the main contributors to the HXRB. In particular, we have shown that with the results of the ISO surveys, which are soon being completed, it will be possible to assess the problems of the local fraction and cosmological evolution of narrow-line AGNs. Also, the problem of the contribution of the AGNs to the IR background has been examined. We found that even in the case of a large number of absorbed sources as implied by the HXRB spectrum, the cosmic infrared background radiation (CIBR) is still a fraction of that expected by normal galaxies. Nevertheless, we predict significant correlation of the HXRB and the CIBR, particularly at around 10–20 \( \mu m \), where the expected ratio between the background produced by the AGNs and that due to galaxies is at a maximum. Also, the assumption that the HXRB is produced by absorbed AGNs implies a large mass density in residual BHs \( \rho_{BH} \approx 4 \times 10^{-4} \, \text{M}_{\odot} \text{Mpc}^{-3} \).

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