AGN dust tori at low and high luminosities

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ABSTRACT
A cornerstone of AGN unification schemes is the presence of an optically and geometrically thick dust torus. It provides the obscuration to explain the difference between type 1 and type 2 AGN. We investigate the influence of the dust distribution on the Eddington limit of the torus. For smooth dust distributions, the Eddington limit on the dust alone is 5 orders of magnitude below the limit for electron scattering in a fully ionized plasma, while a clumpy dust torus has an Eddington limit slightly larger than the classical one. We study the behaviour of a clumpy torus at low and high AGN luminosities. For low luminosities of the order of $10^{42}$ erg s$^{-1}$, the torus changes its characteristics and obscuration becomes insufficient. In the high luminosity regime, the clumpy torus can show a behaviour which is consistent with the “receding torus” picture. The derived luminosity-dependent fraction of type-2-objects agrees with recent observational results. Moreover, the luminosity-dependent covering factor in a clumpy torus may explain the presence of broad-line AGN with high column densities in X-rays.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – quasars: general

1 INTRODUCTION

The widely accepted unification scheme for active galactic nuclei (AGN) proposes that the central accretion disk and broad line region (BLR) are surrounded by a geometrically thick dusty torus (e.g., Antonucci 1993). The dust in the torus obscures the accretion disk and BLR for lines of sight which pass through the torus, while they are visible otherwise. The spectral energy distributions (SED) of most Quasars and AGN in Seyfert galaxies have a pronounced secondary peak in the mid-infrared (e.g., Sanders et al. [1980]; Elvis et al. [1994]), which is interpreted as thermal emission by hot dust in the torus. The dust is heated by the primary optical/UV continuum radiation, and the torus extends from the dust sublimation radius outwards (Barvains 1985). To date, the thermal dust emission from the torus has only been spatially resolved by infrared interferometric techniques for the torus in NGC 1068 (Weigelt et al. [2001]; Jaffe et al. [2004]) and Circinus (Tristram et al. [2006]). The actual geometry and physical properties (e.g., dynamics and dust composition) are, thus, still unknown. In particular, the geometrical thickness, which determines the covering (obscuration) factor, remains a puzzle: Although axisymmetric, rotating gas and dust configurations with cooling will form thin disks, the torus should keep an aspect ratio $H/r \geq 0.5$ for most of the AGN activity phase.

Besides the geometrical thickness, the dynamics of dust in the torus is strongly affected by radiation pressure from the primary AGN luminosity. It has been suggested that the (radiation) pressure by starformation inside the torus may solve the problem of its geometrical thickness (e.g., Ohsuga & Umemura 1999; Wada & Norman 2002). In a competing scenario, the torus consists of a large number of small, self-gravitating, dusty molecular clouds which form a clumpy torus (Krolik & Begelman [1988]; Beckert & Duschl 2004).

In this article, we describe the consequences of AGN radiation pressure for the clumpy torus model. In Sect. 2, we describe the Eddington limit on gas and dust. In Sect. 3 and 4, we introduce a lower and an upper luminosity limit for the torus, respectively. We summarize our results in Sect. 5.

2 THE EDDINGTON LIMIT FOR THE TORUS

In the classical picture, the Eddington limit is defined as the state when gravity of the enclosed mass balances the radiation pressure from the central source, so that

$$L_{\text{edd}} = 4\pi cGM(r) \cdot \frac{m}{\sigma}$$

(1)

Here $G$ is the gravity constant, $c$ is the speed of light, and $m$ and $\sigma$ are the mass and the cross section of the particle which is exposed to the radiation. For a fully ionized plasma around a black hole, the inverse opacity $m/\sigma = \kappa^{-1}$ is dominated by the proton mass and Thomson scattering of electrons. This changes in the region of the torus where dust
is mixed with gas. For reference, we use \( \kappa_0 = \sigma_T/m_p = 0.4 \text{ cm}^2/\text{g} \) for the fully ionized gas. Assuming that gravity is dominated by the black hole mass \( M = M_{\text{BH}} = M_7 \times 10^7 M_\odot \), we obtain the classical Eddington limit
\[
L_{\text{edd}}^{(\text{std})} = 1.26 \times 10^{45} \text{ erg s}^{-1} \cdot M_7
\]

The time-averaged AGN luminosity is expected to scale with the mass accretion rate in the accretion disk by \( \dot{\eta} \). In a stationary scenario, the accretion disk itself is fueled by mass transported through the torus from galactic scales. The mass transport rate through the torus \( \dot{M}_{\text{Torus}} \) is related to \( \dot{M}_{\text{AD}} = \dot{M}_{\text{Torus}} - \dot{M}_{\text{outflow}} \). This relation considers mass loss in an outflow or jet during the accretion process from the torus towards the inner accretion disk. With \( \tau = 1 - \dot{M}_{\text{outflow}}/\dot{M}_{\text{Torus}} \), we obtain
\[
L = \eta \dot{M}_{\text{Torus}} \tau \eta^{2} \dot{M}_{\text{Torus}}^2 \tau^2.
\]

The combination of theory and observation for radiative efficient accretion with outflows suggests \( 0.01 \leq \eta \leq 0.1 \) (e.g., Emmering et al. 1992; Pelletier & Pudritz 1992). In the following we will use a representative value of \( \eta = 0.05 \). From Eqn. (3), we obtain \( \dot{M}_{\text{Torus}} = 0.4 M_\odot \text{ yr}^{-1} \times L_{45} \). Here \( L_{45} \) is the bolometric luminosity in units of \( 10^{45} \text{ erg s}^{-1} \).

We will now investigate the accretion properties for a dusty medium in the AGN torus considering a smooth dust distribution and a clumpy structure, respectively.

### 2.1 Smooth dust distribution

Radiative transfer simulations of AGN dust tori frequently use dust which is smoothly distributed (e.g., Pier & Krolik 1992; Granato & Danese 1994; Schartmann et al. 2005). The radiation which comes from the central AGN directly acts on the dust grains in the torus. The absorption cross section of the dust grains in the optical and UV regime can be approximated by their geometrical cross section \( \sigma = \pi r_\text{Dust}^2 \).

Standard size distributions assume dust grain sizes between 0.025 \( \mu \text{m} \) and 0.25 \( \mu \text{m} \) (e.g., Mathis et al. 1977). Using a typical dust grain density of \( 2 - 3 \text{ g/cm}^3 \), we obtain an opacity \( \kappa_{\text{Dust}} \approx 3 \times 10^4 \kappa_0 \). Using \( \kappa_{\text{Dust}} \) in Eqn. (1), the Eddington luminosity for smoothly distributed dust becomes
\[
L_{\text{edd}}^{(\text{smooth})} = 0.3 - 5 \times 10^{45} \text{ erg s}^{-1} \cdot M_7
\]

Due to the large value of \( \kappa_0 \), the Eddington luminosity decreases by 5 orders of magnitude. As a consequence, typical AGN luminosities of \( 10^{45} \text{ erg s}^{-1} \) would require a black hole mass of \( 10^{12} M_\odot \). This is, however, inconsistent with observed \( M_{\text{BH}}/L_{\text{bol}} \)-ratios (e.g., Kaspi et al. 2000; Woo & Urry 2002). As a consequence the dust cannot be gravitationally bound to the black hole.

The result with the approximated \( \kappa_{\text{Dust}} \) is consistent with recent opacity calculations for a more realistic dust and gas mixture (e.g., Semenov et al. 2003). They show that dust opacities for UV temperatures, which are dominating the AGN accretion disk radiation, are about 4 orders of magnitude larger than the Thomson opacity \( \kappa_0 \). In principle, IR photons coming from more external regions of the torus act as a counter force to the UV photon pressure from the AD. However, the IR opacity of the gas and dust mixture is \( \sim 10^3 \) times smaller than the UV opacity, resulting in an insignificant effect of IR photons when compared to the dominating UV photons. Furthermore, the geometry of the torus causes the diffuse IR torus radiation to act more or less isotropically on the inner wall of the torus (at least in the torus plane), so that a possible IR counter pressure is even weakened. Contrary, it is rather expected that the main effect of the IR photon pressure inside the torus is a vertical thickening (Krolik 2007).

Eqn. (1) considers dust grains which are decoupled from the gas. However, even for a perfect coupling of gas and dust in the torus (no drift of the dust relative to the gas), the usually assumed mass ratio of gas to dust of 100 raises the limit \( L_{\text{edd}}^{(\text{smooth})} \) to only 0.001 of the classical limit in Eqn. (2). The limit \( L_{\text{edd}}^{(\text{smooth})} \) is valid for an optically thin gas dust mixture, while AGN tori are necessarily optically thick, providing self-shielding of most of the torus against the AGN radiation. This creates a radiation pressure gradient at the inner boundary layer (width \( \tau \ll 1 \)) of the torus. The corresponding outward force on this layer is \( L/\dot{L}_{\text{edd}}^{(\text{smooth})} \sim L_{\text{edd}}^{(\text{smooth})} \sim 10^4 \) times stronger than the gravitational pull of the central black hole. This outward force would have to be counterbalanced by an enormous inward pressure gradient in the inner boundary layer.

### 2.2 Clumpy dust torus

An alternative model to smoothly distributed dust was proposed by Krolik & Begelman (1988). They argue that most of the gas and dust in the torus around an AGN has to be arranged in optically thick, self-gravitating clouds.

Vollmer et al. (2004) and Beckert & Duschl (2004) presented a stationary accretion model for the clumpy torus (hereafter: SA model), including relations for torus and dust cloud properties. The main idea behind this model is that clouds are very compact with a large optical depth in the UV due to dust which provides self-shielding against the AGN radiation and allows the clouds interior to be cold. Dust grains on the directly illuminated sides of the clouds are exposed to the AGN and individual dust grains are potentially accelerated and expelled from the cloud due to the radiation pressure. Both magnetic fields and dynamical friction of grains in the gas phase of the cloud (see, e.g., Spitzer 1978, Sec. 9) can prevent this and transfer the momentum to the gas. In a self-gravitating cloud the radiation pressure is therefore received by the whole cloud. Thus, the torus is limited by the radiation pressure from the central AGN acting on the dust clouds instead of single grains, so that we can define a cloud opacity \( \kappa_{\text{cl}} = \pi R_{\text{cl}}^2/M_{\text{cl}} \).

The SA model assumes the clouds to be self-gravitating, so that the free-fall time equals the sound crossing time \( R_{\text{cl}}/c_s \). This provides a linear relation between cloud mass \( M_{\text{cl}} \) and \( R_{\text{cl}} \). These clouds should be stable against tidal forces in the gravitational field of the central black hole. This requires \( R_{\text{cl}}^3/M_{\text{cl}}^2 \leq 2M_{\text{BH}}/M_{\text{cl}} \). When combining both limits (see Beckert & Duschl 2004), one finds an upper limit for the cloud size
\[
R_{\text{cl}, \text{max}} = \frac{\pi}{\sqrt{8G}} \frac{c_s^{3/2}}{M_{\text{cl}}^{1/2}}
\]
and a corresponding mass
\[
M_{\text{cl}} = \frac{\pi^2 c_s^2}{8G} R_{\text{cl}}.
\]
Here \( c_s \) is the cloud-internal speed of pressure waves which is of the order of 1 km s\(^{-1}\). We use this value as the unit for \( c_s \) in the following. This speed characterizes the cloud internal pressure which is required to balance self-gravity, and can be understood as the speed of supersonic turbulence in the clouds. Alternatively, the clouds may be magnetically supported \([1]\). Due to their large cross section, these clouds dominate the absorption, scattering, and IR re-emission. From the relations for \( R_{\text{cl}} \) and \( M_{\text{cl}} \), we get an upper envelope for the opacity of \( \kappa_{\text{cl}} = 0.7 \times 50 \cdot r_{\text{pc}}^2 / (c_s M_{\text{Torus}}^{1/2}) \). The distance from the black hole \( r_{\text{pc}} \) is measured in pc and the speed \( c_s \) in km s\(^{-1}\). For clouds smaller than the shear limit, the opacity \( \kappa_{\text{cl}} \propto R_{\text{cl}} \) becomes smaller. With Eqn. (1), we obtain the Eddington limit for clouds in a clumpy torus, which are directly exposed to the primary AGN radiation,

\[
L_{\text{cold}}^{(cl)} = 1.78 \times 10^{45} \text{ erg s}^{-1} \cdot \frac{c_s M_{\text{Torus}}^{3/2}}{r_{\text{pc}}^2}.
\]

This is of the same order as in the classical Eddington limit (Eqn. 2) and is consistent with observed AGN luminosities and black hole masses. Since \( L_{\text{cold}} \propto \kappa^{-1} \), the Eddington limit for small clouds is even larger than in Eqn. 2.

Eqn. (7) shows that \( L_{\text{cold}}^{(cl)} \propto r_{\text{pc}}^{-3/2} \). This implies that at larger distances, self-gravitating clouds which are directly exposed to the AGN radiation become unbound by the radiation pressure. Thus, distant clouds have to be shielded against the AGN radiation by clouds at small radii. As a consequence, there should be no significant vertical flaring for a clumpy torus; i.e., we expect \( H/r \approx \text{const} \). Further consequences of this behaviour will be discussed in Sect. 4.

### 3 THE TORUS AT LOW AGN LUMINOSITIES

In the previous section, we argued that the Eddington limit for clumpy dust tori is well in agreement with the range of observed AGN luminosities and black hole masses. To be clumpy, a torus requires a small volume filling factor \( \Phi_V \ll 1 \) for the dusty clouds. In the context of a SA model, Beckert & Duschl (2004) find a mass transport rate through the torus \( \dot{M}_{\text{Torus}} = 3 \pi \nu \Sigma \), where \( \nu = 1 + \pi^2 \kappa^2 H_{\text{Edd}}^2 \), is the effective viscosity for a torus and \( \Sigma \) is the surface density. For an obscuring torus, the scale height, \( H \), cannot be smaller than the mean free path of clouds \( \lambda = (4/3)R_{\text{cl}} / \Phi_{V} \).

Otherwise the torus would become transparent for AGN photons. The parameter \( \tau \) in the viscosity prescription measures the ratio \( \tau = l / H \). The geometric thickness of the torus and the viscosity is maximised for \( \tau = 1 \). For \( H \gg l \) the cloud density in the torus growth rapidly and the torus would collapse to a thin disk. We therefore adopt \( H = l \) for a working model. After replacing the mean free path by the appropriate expression from Beckert & Duschl (2004), we get \( \Phi_V \) in terms of \( M_{\text{Torus}} \).

\[
\Phi_V = \frac{\pi^{7/4}}{\sqrt{6G}} \cdot \frac{c_s^{3/2}}{M_{\text{Torus}}^{1/2}}.
\]

The volume filling factor only depends on the mass transport rate through the torus, which we parametrized by \( \dot{M}_{\text{Torus}} = 0.4 M_\odot \text{yr}^{-1} \cdot L_{\odot}^{-1} \cdot (\eta/0.05)^{-1} \) (see Sect. 2). By substituting \( \dot{M}_{\text{Torus}} \), we obtain a hard lower luminosity for the existence of an obscuring torus according to the SA model,

\[
L_{\text{low}} = 5 \times 10^{42} \text{ erg s}^{-1} \cdot \left( \frac{\eta}{0.05} \right)^{1/2}
\]

at which \( \Phi_V = 1 \). For clumpy obscuring tori as described, it is necessary that the AGN luminosity is \( L \gg L_{\text{low}} \). If \( L \gg L_{\text{low}} \), the volume filling factor becomes \( \Phi_V \rightarrow 1 \). At this point, the SA model would require that the torus collapses to a geometrically thin disk. As a consequence, most of the dust would be driven away (see Sect. 2). It is, however, known that this situation can be avoided: Lower luminosities go along with lower accretion rates. Vollmer et al. (2004) showed that for low mass accretion rate, a clumpy and almost transparent (\( l \approx H \)) circumnuclear disk (CND) can form similar to what has been found around the central black hole in our Galaxy (Güsten et al. 1987). The difference between the clumpy torus and the CND is that the latter one loses most of its obscuration properties while there can still be IR reprocessing.

Several observational studies show that at about \( 10^{42} \text{ erg s}^{-1} \), the \( L_{\text{bol}} - L_{\text{MIR}} \) or \( L_{\times} - L_{\text{MIR}} \) relation show a significant change in behaviour compared to higher luminosities (e.g., Lutz et al. 2004; Horst et al. 2006). Apparently, the main source of MIR emission at \( L \approx 10^{42} \text{ erg s}^{-1} \) is not the proposed, geometrically thick torus anymore.

A similar low-luminosity limit has been found for models where the dust clouds are not produced in a torus but released into a wind from an accretion disk (Elitzur & Shlosman 2004). The cutoff at lower luminosities is a result of the fact that the mass outflow rate in the wind cannot exceed the mass accretion rate in the disk. Taking the same \( \tau \) and \( \eta \) as used in Elitzur & Shlosman (2006), we obtain \( L_{\text{low}} = 2 \times 10^{42} \text{ erg s}^{-1} \).

### 4 THE DUST TORUS IN THE HIGH LUMINOSITY REGIME

In Sect. 2.2, we have shown that the Eddington luminosity for clouds in the clumpy torus, \( L_{\text{cold}}^{(cl)} \), depends on the cloud-AGN distance as \( r^{-3/2} \). A large fraction of AGN radiate close to or at the classical Eddington limit for Thomson scattering (Mclure & Dunlop 2001). We therefore scale the actual luminosity to the classical limit \( L = L_{\text{cold}}^{(cl)} \ell_{\text{Edd}} \), where \( \ell_{\text{Edd}} \ll 1 \) is the Eddington ratio for the AGN. Once \( L_{\text{cold}}^{(cl)} \) becomes smaller than \( L \), the clouds of corresponding \( R_{\text{cl}} \) which are directly exposed to the radiation of the central source can no longer resist the radiation pressure. This defines the condition \( L / L_{\text{cold}}^{(cl)} < 1 \) for the existence of dust clouds of radius \( R_{\text{cl}} \) in the AGN radiation field. Since \( L_{\text{cold}}^{(cl)} \) is \( r \)-dependent, we obtain a maximum distance from the AGN, \( r_{\text{max}}(R_{\text{cl}}) \), at which the largest clouds can withstand the radiation pressure:

\[
r_{\text{max}}(R_{\text{cl}}) = 1.3 \text{ pc} \cdot \ell_{\text{Edd}}^{2/3} c_s^{2/3} \cdot M_{\text{Torus}}^{1/3} \cdot \left( \frac{R_{\text{cl}}}{R_{\text{cl, max}}} \right)^{-2/3}
\]
The factor \(R_{\text{cl}}/R_{\text{cl, max}}\) ≤ 1 accounts for different cloud radii \(R_{\text{cl}}\) up to the sheer limit \(R_{\text{cl, max}}\) (see Eqn. (5)). As mentioned in Sect. 2.2, clouds at distances \(r > r_{\text{max}}\) need to be shielded, so that no vertical flaring should occur beyond \(r_{\text{max}}\). We want to note that \(r_{\text{max}}\) does not refer to an outer radius of the torus. It relates the maximum possible size of a dust cloud to the radiation pressure from the central AGN.

A proper scaling of the limiting radius, \(r_{\text{max}}\), is in units of the dust sublimation radius which presumably sets the inner radius of the torus. The sublimation radius is depending on the actual dust chemistry and grain sizes. A well-approximated estimation of the \(r_{\text{sub}}\) was introduced by [Barvainis 1987]), providing \(r_{\text{sub}} = 0.4 \, \text{pc} \times \frac{L_{\text{edd}}^{1/2}}{M_{\text{sub}}^{1/2} T_{\text{sub}}^{0.05}}\), where sublimation of graphite grains of radius 0.05 \(\mu\text{m}\) and a sublimation temperature of 1500 K is assumed. For different grain sizes and chemistry, the sublimation radius and the temperature exponent change. Thus, in the case of silicate grains with similar grain size, the sublimation radius is larger by about a factor of about 3. While the actual chemistry, grain sizes and sublimation temperatures around AGN are still a matter of debate (e.g., [Barvainis 1992; Sitko et al. 1992; Kishimoto et al. 2007]), reverberation measurements of type 1 AGN support \(r_{\text{sub}} \propto L^{1/2}\) (Suganuma et al. 2006). In the following, we will use the simplified relation \(r_{\text{sub}} = 0.5 \, \text{pc} \times L_{45}^{1/2}\), keeping in mind the uncertainty due to the actual dust mixture.

Finally, this allows for a comparison of \(r_{\text{max}}\) with the inner boundary of the torus:

\[
\frac{r_{\text{max}}}{r_{\text{sub}}} = 2.3 \cdot c_{\text{d}}^2 / L_{45}^{1/6} \cdot \frac{\ell_{\text{edd}}}{R_{\text{cl, max}}} \end{equation}
\]

Interestingly, \(r_{\text{max}}/r_{\text{sub}}\) is approximately of the order of unity. That means that at \(L \gtrsim L_{45}\), the maximum dust cloud size can be limited by the radiation pressure rather than the sheer limit. Which mechanism dominates for an individual AGN depends on its actual \(L/M\). We will, thus, distinguish between radiation-limited tori (AGN with higher \(\ell\) or \(L\)) and sheer-limited tori (AGN with lower \(\ell\) or \(L\)) in the following.

An effect of Eqn. (11) is a change in obscuration properties with higher luminosities. In Sect. 3, we briefly summarized the results from the SA model which requires \(H = l = 4/3 R_{\text{cl}}/c_{\text{V}}\). Contrary to the lower AGN luminosities, \(R_{\text{cl}}\) is now defined by the radiation limit (Eqn. (11)) instead of the sheer limit (Eqn. (5)). From \(R_{\text{cl}} \propto L^{-1/4}\) (Eqn. (11)) and \(c_{\text{V}} \propto M_{\text{Torus}}^{1/2} \propto L^{-1/2}\) (Eqn. (5)), we obtain \(H \propto L^{1/4}\). Since the torus is expected to have \(H/R = \text{const}\), the thickness of the torus is determined at the reference distance \(R = r_{\text{sub}} \propto L^{1/2}\). This results in an average thickness of the torus,

\[
H/R \propto L^{-1/4}. \end{equation}
\]

Thus, we expect to see more type 1 AGN at higher luminosities for objects which have radiation-limited cloudy tori.

This result can be interpreted in the framework of the “receding torus” (Lawrence 1991): It has been observed that for high-luminosity sources, the observed hydrogen column density is lower than in low-luminosity sources (e.g., Ueda et al. 2003; Barger et al. 2005; La Franca et al. 2005; Akylas et al. 2006). This is interpreted as a decrease of the covering factor of the torus with luminosity; i.e., \(H/R\) appears to be anti-correlated with \(L\). Recently, Simpson (2003) analysed the luminosity-dependence of the type 1 and type 2 AGN fraction by combining the results from different surveys. While the original receding torus (Lawrence 1991) predicts a type-2-fraction \(f_2 \propto L^{-1/2}\), a better fit was found for a situation where the height of the torus depends on luminosity. From Eqn. (12), we would approximately expect \(f_2 \propto L^{-0.27}\) for radiation-limited dust tori. This is remarkably close to the correlation \(f_2 \propto L^{-0.27}\) derived by Simpson. We note, however, that for objects with low \(\ell_{\text{edd}}\), the \(L^{-1/4}\)-dependence should not hold but can even be inverted (see Eqn. cludradius). This would imply that it depends on the actual AGN sample properties if a receding torus is observed or not.

Several authors noted that the UV-to-IR dust extinction in AGN is lower than what would be inferred from the X-ray column density, in particular referring to AGNs showing broad-lines in the optical and significant absorption in the X-rays (e.g., Wilkes et al. 2002; Perola et al. 2004; Barger et al. 2003). In the clumpy torus model, the AGN’s X-ray emission region is completely obscured by an average number, \(N\), of optically thick clouds along a line of sight passing through the torus. Since the size of the X-ray source is smaller than the typical cloud radius, \(R_{\text{X}} < R_{\text{cl}}\), the X-ray column density is \(N_{\text{X}} \approx N_{\text{cl}}\), where \(N_{\text{cl}}\) denotes the column density of an individual cloud. On the other hand, the BLR is only fractionally (and statistically) obscured by a number of \(N\) optically thick clouds, since \(R_{\text{BLR}} > R_{\text{cl}}\). As a result, the average optical depth in the optical wavelength range, \(\tau_{\lambda}\), can be approximated by \(\tau_{\lambda} \approx N_{\text{X}} / N_{\text{BLR}}\). Thus, the inferred optical depth from the X-rays, \(N \cdot \tau_{\lambda}\), overestimates the measured optical depth \(\tau_{\lambda} \approx N_{\text{X}} \cdot \tau_{\text{BLR}}\). This effect should become stronger at higher AGN luminosities when the clumpy tori become radiation-dominated, since \(N \propto L^{-1/4} \propto L^{-1/4}\). Actually, Perola et al. (2004) report that \(\sim 10\%\) of their observed broad-line AGN show high column densities, all of them having X-ray luminosities \(L_{\text{X}} > 10^{44} \text{erg s}^{-1}\).

5 SUMMARY

We studied the effect of dust on the Eddington limit in the molecular dusty torus of an AGN. While the Eddington limit for smooth dust distributions is approximately 5 orders of magnitudes smaller than the classical Eddington limit for a fully ionized plasma, a clumpy dust torus provides a similar \(L_{\text{edd}} - M_{\text{BH}}\)-relation as the classical one, and is in good agreement with observed luminosities and black hole masses. The idea of a clumpy torus is based on self-gravitating, optically thick dust clouds which are limited in size by the sheer of the gravitational potential of the central black hole. In the framework of this model, we were able to derive a low-luminosity limit for the existence of an obscuring clumpy torus, which is of the order of \(L \sim 10^{42} \text{erg s}^{-1}\). Below this limit, the physical and geometrical properties of the torus change significantly. Furthermore, we investigated
the behaviour of the clumpy torus at high luminosities. We found that the largest clouds in the torus become gravitationally unbound to the central black hole if the AGN radiates close to the classical Eddington limit. In such a case, the dust clouds in the torus are no longer limited in size by the shear of the gravitational potential but by the AGN luminosity. The effective scale height of the radiation-limited tori decreases with luminosity, $H/R \propto L^{-1/4}$. The resulting $L$-dependence for the fraction of type 2 AGN, $f_2 \propto L^{-0.25}$, is consistent with an analysis of several AGN surveys by Simpson (2003). We showed that the clumpy torus can account for broad-line AGN with high X-ray column densities, and that more such objects should be found at high rather than at low luminosities.

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