Cooling Timescale of Dust Tori in Dying Active Galactic Nuclei

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Abstract

We estimate the dust torus cooling timescale once the active galactic nucleus (AGN) is quenched. In a clumpy torus system, once the incoming photons are suppressed, the cooling timescale of one clump from $T_{\text{dust}} = 1000$ K to several 10 K is less than 10 years, indicating that the dust torus cooling time is mainly governed by the light crossing time of the torus from the central engine. After considering the light crossing time of the torus, the AGN torus emission at 12 $\mu$m becomes over two orders of magnitude fainter within 100 years after the quenching. We also propose that those “dying” AGNs could be found using the AGN indicators with a different physical scale $R$ such as 12 $\mu$m band luminosity tracing AGN torus ($R \sim 10$ pc) and the optical [O III] $\lambda 5007$ emission line tracing narrow line regions ($R = 10^{2.5-4}$ pc).

Key words: galaxies: active – galaxies: nuclei – infrared: galaxies

1. Introduction

Dust is the cornerstone of the unified view of active galactic nuclei (AGNs). The unified model of AGNs (e.g., Antonucci & Miller 1985) proposes that all AGNs are essentially the same; all types of AGNs have accretion disks, broad/narrow emission line regions, and those central engines are surrounded by optically and geometrically thick dust “tori” (Krolik & Begelman 1986).

Since the torus absorbs optical and ultraviolet photons from the accretion disk easily, the torus is heated and finally re-emits in the mid-infrared band. X-ray emission also arises as inverse Compton scattering, where the source photons could originate from the accretion disk. The strong luminosity correlations of AGNs between hard X-ray and mid-infrared emission observationally support that the mid-infrared band is a good indicator of AGN torus emission (e.g., Gandhi et al. 2009; Levenson et al. 2009; Asmus et al. 2011, 2015; Ichikawa et al. 2012, 2017;Mateos et al. 2015; García-Bernete et al. 2016).

Recent observations, however, reported interesting populations of AGNs. They show the AGN signatures in the larger physical scale with $>10^2-10^5$ pc scale (e.g., narrow line regions; NLRs and/or radio jets; Scheuer 1995; Bennert et al. 2002), but lack the AGN signatures in the smaller physical scales with $<10$ pc (e.g., lack of X-ray emission, the emission from dust tori, and the radio cores). This population is thought to be in the transient stage where they were active in the past, but now the central engine seems quiescent. They are called fading AGNs or dying AGNs (e.g., Schawinski et al. 2010; Schirmer et al. 2013; Schweizer et al. 2013; Ichikawa et al. 2016; Menezes et al. 2016; Sartori et al. 2016; Schirmer et al. 2016; Keel et al. 2017).

The large-scale AGN signature is also a good tool to constrain the AGN quenching time. IC 2479 is one of the first fading AGNs discovered through the galaxy zoo project (Lintott et al. 2008). Lintott et al. (2009) first mentioned that high ionization lines including [O III] $\lambda 5007$ are bright in the [O III] blob, while the [O III] emission power around the AGN core is orders of magnitude weaker, suggesting that the AGN is fading. Schawinski et al. (2010) confirmed this hypothesis through the X-ray observations with XMM-Newton and Suzaku. Considering the distance from the central engine to the [O III] blobs and input power, they estimated that the central engine of IC 2479 faded over two orders of magnitude within $10^4$ years. Ichikawa et al. (2016) used a jet lobe size for estimating the upper limit of the quenching time of the dying AGN. Assuming a jet angle to the line of sight of $90^\circ$ and a typical expansion, the kinematic age of the radio jets is estimated to be $6 \times 10^6$ year. Therefore, the current understanding is that AGNs reduce their luminosity over two orders of magnitude within $10^4$ year, or even faster.

On the other hand, the size of the AGN dust torus is well suited to our human timescale. Recent mid-infrared high spatial resolution ($\sim 0.3-0.7$ arcsec) observations have constrained the torus size of $<10$ pc (e.g., Packham et al. 2005; Mason et al. 2006; Radomski et al. 2008; Ramos Almeida et al. 2009; Alonso-Herrero et al. 2011; Ichikawa et al. 2015). Furthermore, current mid-infrared interferometry observations have revealed that a nearby AGN torus has a size of several parsecs (e.g., Jaffe et al. 2004; Raban et al. 2009; Höning et al. 2012, 2013; Burtscher et al. 2013; Tristram et al. 2014; López-Gonzaga et al. 2016). Detecting the decline of the torus emission compared to a large-scale feature such as NLR allows us to find a fresh quenching AGN within $\sim 30$ years. To achieve this goal, it is crucial to estimate the torus cooling time quantitatively once the photon flux from the central engine becomes negligible. In this paper, for the first step, we report an estimation of the cooling time of AGN torus once the central engine is shut off in a simple assumption.

2. Model

Since the AGN torus is thought to be composed of a number of individual clumps, the cooling timescale of the dust torus is characterized by that of individual clumps unless the radiative interactions between clumps are neglected. As we discuss in Section 3.1, the radiative interaction is expected to be less important in the cooling timescale. In this section, first, we describe the cooling timescale of an individual clump and show that the clump cools down within $\sim 10$ years once the clump
heating photons are lost. Second, we calculate the spectral energy distribution (SED) of the AGN torus and estimate the attenuation of the flux in the mid-infrared wavelength as time goes by.

2.1. Physical Properties of the Torus Clump

We describe physical properties of the clump in the torus. The idea of the torus clump was first proposed by Krich & Begelman (1988), and then the model was sophisticated by many authors (e.g., Beckert & Deuscher 2004; Höhng & Beckert 2007; Namekata et al. 2014). The basic idea of the torus clump here is mainly compiled in Vollmer et al. (2004).

The clump should be gravitationally bounded, and therefore the mass of the clump $M_c$ is thought to be larger than the Jeans mass $M_J$:

$$ M_c \geq M_J = \frac{\pi^{5/2}}{6} \frac{c_s^3}{G^{3/2} \rho_0^{1/2}}, \tag{1} $$

where $G$ is the gravitational constant, $c_s$ is the speed of sound, and $\rho_0$ is the gas density of the clump. In addition, the clump radius $R_c$ should be smaller than the tidal radius $R_t$:

$$ R_c \leq R_t = \left( \frac{M_c}{3M_{BH}} \right)^{1/3} r, \tag{2} $$

where $r$ is a distance from the black hole to the clump and $M_{BH}$ is the black hole mass in the central engine. Using $\rho_0 = 3M_c/4\pi R_c^3$, Equation (1) can be reduced to

$$ M_c = \frac{\pi^2 c_s^2}{3G} R_c. \tag{3} $$

Substituting Equation (3) into (2), we obtain

$$ R_c = \frac{\rho c_s}{3\sqrt{GM_{BH}}} r^{3/2}. \tag{4} $$

$$ = 4.8 \times 10^{-3} \left( \frac{c_s}{3 \text{ km s}^{-1}} \right) \left( \frac{r}{1 \text{ pc}} \right)^{3/2} \left( \frac{M_{BH}}{10^{8} M_{\odot}} \right)^{1/2} \text{ pc}. \tag{5} $$

It follows from Equations (3) and (4) that the mass of the marginally stable clump is

$$ M_c = \frac{\pi^3}{9} \frac{c_s^3}{G^{3/2} M_{BH}^{1/2}}. \tag{6} $$

$$ = 33 \left( \frac{c_s}{3 \text{ km s}^{-1}} \right)^3 \left( \frac{r}{1 \text{ pc}} \right)^{3/2} \left( \frac{M_{BH}}{10^{8} M_{\odot}} \right)^{-2} M_{\odot}. \tag{7} $$

The average hydrogen number density $n_H$ of one clump is

$$ n_H = 3 M_c / 4\pi R_c^3 m_H = 2.6 \times 10^{9} \text{ cm}^{-3}, $$

where $m_H$ is the hydrogen mass. In this study, we assume the homogeneous spherical clump for simplicity.

2.2. Cooling Timescale of the Individual Clump

Suppose the size distribution of dust grains obeys the power-law size distribution (Mathis et al. 1977; Draine & Lee 1984),

$$ n(a)da = A n_H a^2 da \quad (a_{\text{min}} < a < a_{\text{max}}), \tag{8} $$

where $n(a)$ is the distribution function of grain size, $a$ is a grain radius, $A$ is a normalization factor and $n_H$ is the number density of H nuclei, and subscript $i$ denotes the silicate or the graphite.

Denote $E_{c,d}$ by the internal energy of a dust clump, then it can be described as follows:

$$ E_{c,d}(T_d) = M_c g_d \frac{\sum_{i} A_i \int_{T_i}^{T_d} dT_i C_i(T_i)}{\sum_{i} A_i \rho_i}, \tag{9} $$

where $C_i(T_d)$ is the heat capacity per unit volume, $T$ is the temperature of a clump, $M_c g_d$ is the mass of the dust clump, and $g_d$ is a dust-to-gas mass ratio. For the sake of simplicity, we assumed an individual clump has a uniform temperature. That is, noting that the dust temperature at the outer and inner regions within a clump may differ. However, this temperature difference does not significantly alter internal energy and the cooling curve of a clump. Hence, in this paper, we adopt single temperature approximation for an individual clump.

For the model of heat capacities, we adopt Draine & Li (2001),\(^5\) then

$$ C_{\text{gra}} = (N_c - 2) k_B \left[ f(T_{863 \text{ K}}) + 2 f(T_{2504 \text{ K}}) \right], \tag{10} $$

$$ C_{\text{sill}} = (N_s - 2) k_B \left[ 2 f(T_{500 \text{ K}}) + f(T_{1500 \text{ K}}) \right], \tag{11} $$

where

$$ f_n(x) = n \int_0^1 \frac{y^n dy}{\exp(y/x) - 1}, f'_n(x) = \frac{d}{dx} f_n(x). \tag{12} $$

$N_c$ and $N_s$ are the number density of carbon and atoms for graphite and silicate, respectively, assuming $\rho_{\text{gra}} = 2.26 \text{ g cm}^{-3}$ and $\rho_{\text{sill}} = 3.5 \text{ g cm}^{-3}$ reduce to $N_c = 1.5 \times 10^{23} \text{ cm}^{-3}$ and $N_s = 8.5 \times 10^{22} \text{ cm}^{-3}$, respectively.

Next, we investigate how the individual clump cools as time goes by. If the dust clump is optically thick, internal energy of the clump will be released through its photosphere, and then the cooling rate will be proportional to the surface area of the clump. Hence, we expect the cooling rate of the optically thick clump to be approximately $4\pi R_c^2 \sigma_{SB} T^4$, where $T$ is the temperature of the clump and $\sigma_{SB}$ is a Stefan–Boltzmann constant. On the other hand, if the dust clump is optically thin, the cooling rate should be the same as that of single dust grains. Based on the above consideration, we adopt the energy equation of the individual clump for arbitrary optical depth as follows.

$$ \frac{dE_{c,d}}{dt} = -4\pi R_c^2 \langle Q_c \rangle_T \sigma_{SB} T^4 + \int_{V_{\text{clump}}} n_i \eta_i \Gamma_{g-d} dV, \tag{13} $$

where $R_c$ is the radius of a clump, $n_i \Gamma_{g-d}$ is the energy exchange between gas and dust, and $\langle Q_c \rangle_T$ denotes the physical quantity $Q_c$ to be averaged over the Planck function with temperature $T$. $\Gamma_{g-d} = [1 - e^{-\tau_c}]$ is the emission efficiency of a clump, where $\tau_c$ is the optical depth for absorption of a clump defined by

$$ \tau_c = \sum_i \int ds \int_{a_{\text{min}}}^{a_{\text{max}}} d\alpha_i \kappa_i(a) m_i \kappa_{i,s}(a), \tag{14} $$

where $m$ is the mass of the dust grain, and $\kappa_i(a)$ is the absorption opacity of the dust grain. From Equations (14) and

\(^5\) There is a typographical error of Equation (10) of Draine & Li (2001) as pointed out in Li & Draine (2002).
where \( m_{H} \) is the hydrogen mass, \( f_d \) is the dust-to-gas mass ratio, and

\[
\eta_{i} \equiv \frac{\int d\alpha a^{3+p} \kappa_{i}(\alpha)}{\int d\alpha a^{3+p}}.
\]

The dust-to-gas mass ratio \( f_d \) can be described as, for \( p = -4 \),

\[
f_d = \frac{4\pi}{3m_{H}} \left( \frac{a_{\max}^{4+p}}{a_{\min}^{4+p}} \right) \sum A_i \rho_i.
\]

The energy exchange between gas and dust can be written as

\[
n_{g} T_{g}^{2} = \sum_{i} \int n_{i}(\alpha) d\alpha a^{4+p} n_{\text{th}}(\alpha) (2k_{B} T_{g} - 2k_{B} T_{d}).
\]

Using Equation (8), we find

\[
n_{g} T_{g}^{2} = \frac{2\pi}{(3 + p)} k_{B} \alpha_{T}(T_{g} - T_{d}) n_{\text{th}}^{2} V_{h}
\times a_{\min}^{3+p} \left( \frac{a_{\max}^{4+p}}{a_{\min}^{4+p}} - 1 \right) \sum A_i \rho_i,
\]

where \( \alpha_{T} \) is the accommodation coefficient, \( v_{h} \) is the thermal velocity of gas, and \( T_{g} \) is the gas temperature. We have averaged over the grain size distribution. In this paper, we assume \( \alpha_{T} = 0.15 \) (e.g., Tielens 2005). Since we have assumed uniform temperature and density structure in the clump, \( n_{g} T_{g}^{2} \) is constant within the cloud. Therefore, we obtain

\[
\frac{dT_{d}}{dt} = \beta \left\{ -4\pi R_{c}^{2} (\Omega_{d}) T_{C} \sigma_{B} T_{d}^{4} + n_{g} \frac{2\pi R_{c}^{2}}{3} \right\}
\]

\[
\beta = \frac{1}{M_{g} \rho_{d}} \sum A_i \rho_i (T_{d}).
\]

The abundance ratio of silicates and graphite is set as \( A_{\text{sil}}/A_{\text{gra}} = 1.12 \) (Draine & Lee 1984). This corresponds to 53\% of silicate grains, and the other 47\% for graphite in volume. The upper and lower cut-off to the size distribution is assumed to be \( a_{\min} = 0.005 \mu m \) and \( a_{\max} = 0.25 \mu m \), and the slope adopted is \( p = -3.5 \) (Mathis et al. 1977). Since the dust-to-gas ratio \( f_d \) in AGNs is still under debate (e.g., Maiolino et al. 2001), we use the galactic ISM value of \( f_d = 0.01 \) (e.g., Tielens 2005) throughout this paper. The dust grain is assumed to be spherical; thus, optical properties can be calculated by using the Mie theory (e.g., Bohren & Huffman 1983). For the dielectric function of silicates and graphites, we adopt Draine & Lee (1984), Laor & Draine (1993), Weingartner & Draine (2001), Draine (2003), Draine & Lee (1984), and Aniano et al. (2012), respectively. Since graphite is a highly anisotropic material, optical properties depend on the direction of incident \( E \) fields with respect to the basal plane of graphite. We assume randomly oriented graphite grains, and hence, we can use the so-called “\( \frac{1}{2} - \frac{1}{2} \) approximation” (e.g., Draine 1988); \( \kappa_{\text{gra},E} = 2k_{g}\kappa_{E} E(\mathbf{E} \cdot \mathbf{c})^{2} \), \( \kappa_{\text{gra},c} = 2k_{g}\kappa_{E} E(\mathbf{E} \cdot \mathbf{c})^{2} \), where \( E \) is the incident electric field and \( c \) is a normal vector to the basal plane of graphite. To estimate the free-electrons contribution to the dielectric function for graphite with \( E \parallel c \), we adopt the two-component free-electrons model introduced by Aniano et al. (2012). For free-electron models of \( E \perp c \), we still adopt the model of Draine & Lee (1984).

Since the gas–dust collision term depends on the gas temperature, the energy equation of gas should also be solved. Denote \( E_{c,g} \) by the internal energy of the gas in the clump, then the energy equation for gas can be written as

\[
\frac{dE_{c,g}}{dt} = -\int_{\text{cloud}} \{ n_{g} \Gamma_{g-d} + n_{g}^{2} \lambda_{\text{line}} \} dV,
\]

where \( n_{g} \Gamma_{g-d} \) and \( n_{g}^{2} \lambda_{\text{line}} \) represent the energy exchange between gas and dust and by line cooling, respectively. Note that \( n_{g} \Gamma_{g-d} \) has a positive sign when the gas temperature is higher than the dust temperature. We have ignored the compression heating since the free-fall timescale of the clump is longer than the cooling timescale of the clump, e.g., \( t_{ff} = (3\pi/32G\rho_{g})^{-1} = 9.6 \times 10^{2} \) year for the clump of \( R_{c} = 5 \times 10^{3} \) pc and \( M_{c} = 33 M_{\odot} \). The radiative cooling rate of the transition from level \( u \) to level \( l \) of some species \( x \) is written as (e.g., Tielens & Hollenbach 1985)

\[
n_{g}^{2} \lambda_{x}(\nu_{ul}) = n_{A} A_{ul} h_{ul} \nu_{ul} \beta(\tau_{d}) \left\{ (S_{l}(\nu_{ul}) - P(\nu_{ul})/S_{u}(\nu_{ul})) \right\},
\]

where \( n_{x} \) is a population density at level \( u, \beta(\tau_{d}) \) is the escape probability, \( S_{u}(\nu) \) is the source function, and \( P(\nu) \) is the background radiation field. As a background radiation, we assume the ambient thermal radiation from dust grains, and then

\[
P(\nu_{ul}) = B(\nu_{ul}, T_{d})[1 - \exp(-\tau_{d})],
\]

where \( \tau_{d} \) is calculated using Equation (14). Since we have assumed a homogeneous spherical clump, the escape probability averaged over line profile and over the cloud volume can be approximately given by (Draine 2011)

\[
\beta(\tau_{d}) \approx \frac{1}{1 + 0.5\tau_{0}},
\]

where \( \tau_{0} \) is an optical depth at line center, given by

\[
\tau_{0} = \frac{g_{u} A_{ul} \lambda_{ul}}{g_{l} 4(2\pi)^{3/2} \sigma_{v} R_{c}} \left( 1 - n_{u} g_{u}/n_{l} g_{l} \right).
\]

Here we assumed that gas motion is a Maxwellian one-dimensional distribution with the velocity dispersion of \( \sigma_{v} = (k_{B} T_{d}/m_{H})^{1/2} \).

Gas is assumed to be ideal, and hence, the equation of state becomes \( e_{g} = n_{g} k_{B} T_{g} / (\gamma - 1) \). As a result, we find

\[
\frac{dT_{g}}{dt} = -\frac{(\gamma - 1)}{n_{g} k_{B}} \left( n_{g} \Gamma_{g-d} + n_{g}^{2} \lambda_{\text{line}} \right),
\]

where \( \gamma \) is a specific heat ratio and we adopt \( \gamma = 5/3 \). In this paper, we assume the local thermal equilibrium (LTE) to obtain the level populations. As molecular species, we adopt H$_{2}$, CO, and H$_{2}$O because these molecules are abundant in the AGN dust tori. Note that H$_{2}$O becomes abundant at a relatively hot inner region of dust tori, because H$_{2}$O molecules form via a neutral–neutral reaction whose energy barrier is \( \approx 1000 \) K, and the reaction is effective at \( > 300 \) K (Harada et al. 2010). We adopt the molecular fractional abundances with respect to \( n_{H} \) as...
\[ \lambda_{H_2} = 0.5, \quad \lambda_{CO} = 3.0 \times 10^{-5}, \quad \text{and} \quad \lambda_{H_2O} = 1.4 \times 10^{-4} \text{ at 3 pc from the black hole (Harada et al. 2010). We adopt the data of line parameters in the Leiden Atomic and Molecular Database LAMDA}\(^6\) (Schöier et al. 2005) and H\(_2\) line parameters in Wagenblast & Harquist (1988) and Nomura & Millar (2005). We use a part of the RATRAN code\(^7\) (Hogerheijde & van der Tak 2000) in order to read the molecular data for calculating the line cooling.

In Figure 1, we plot the change of dust and gas temperature of the individual clump. Figure 1 shows that the clump cools down to tens of Kelvin within \(\sim 10\) years. Dust temperature drops quickly until \(t \sim 10^3\) s after the heating photon supply ends, and then it reaches a plateau phase, where the radiative cooling and collisional heating of gas particles are balancing. Therefore, dust grains cannot cool down to tens of Kelvin unless the dust clump gas cools down. The gas temperature starts to decrease at \(t \sim 10^5\) s due to molecular line cooling that is mainly dominated by \(H_2O\). Even in the absence of line cooling, the gas clump will be cooled due to dust radiation via gas–dust collisions. As a result, dust temperature drops to tens of Kelvin within \(\sim 10\) years. It is worth noting that equilibrium dust temperature at the plateau phase depends on the gas density. This indicates that clumps at the outer region cool down faster than the inner clumps since they have lower gas density. This result indicates that the cooling timescale of dust tori is slightly shorter than the light crossing time with an order of 10 years of the dust torus size. Therefore, we conclude that the dust cooling timescale in the torus is mainly governed by the light crossing time.

### 2.3. SED of Dust Tori

To reproduce the torus SED, we assume smooth distribution of the dust density for simplicity. The SED of AGN torus is obtained by using a two-layer model (Chiang & Goldreich 1997; Chiang et al. 2001). In this model, the optically thick disk is divided into two regions, the surface layer where the dust grains are directly irradiated by the AGN, and the interior layer where the dust grains are indirectly heated by the AGN, in other words, they are heated by the thermal emission of directly irradiated dust grains at the surface layer. The resultant SED can be obtained by superposing the flux from the surface layer (Equation (32)) and interior layer (Equation (33)).

We assume that the torus is axisymmetric, and the surface density of dust grains obeys the simple power-law function, \(\Sigma_d = 3.5 \times 10^{-2} (r/1\, \text{pc})^{-1.5} \text{ g cm}^{-2}\). The inner and outer radii were obtained by using a two-layer model\(^8\) (Barvainis 1987; Kishimoto et al. 2011; Koshida et al. 2014), and \(r_{\text{cut}} = 10(L_{\text{AGN}}/10^{45}\, \text{erg s}^{-1})^{0.5}\) pc (Kishimoto et al. 2011; García-Burillo et al. 2016; Imanishi et al. 2016), respectively. The opening angle of the torus is assumed to be 45 degrees, and then the grazing angle is \(\alpha \approx r_{\text{in}}/r\). The opacity of a mixture of silicate and graphite grains is obtained by averaging the absorption efficiency of them weighted for the volume fraction of 53% and 47% for silicate and graphite, respectively.

The temperature of directly irradiated dust grains by the AGN is

\[
T_{\text{ds}}(r, \alpha) = \left( \frac{L_{\text{AGN}}}{16\pi r^2 \sigma_{SB} \langle Q_{\text{abs}}/\langle Q_{\text{abs}}\rangle_{\text{AGN}}} \right)^{1/2},
\]

where \(r\) is a distance from the AGN, and \(L_{\text{AGN}} = 10^{45}\, \text{erg s}^{-1}\) is the AGN luminosity. \(\langle Q_{\text{abs}}\rangle_{\text{AGN}}\) is an absorption efficiency with respect to the incoming AGN photons, defined by

\[
\langle Q_{\text{abs}}\rangle_{\text{AGN}} = \int Q_{\text{abs}} f_{\alpha} \, d\lambda,
\]

where \(f_{\alpha} = F_{\alpha}/F_{\text{AGN}},\) and \(F_{\text{AGN}} = \int_0^{\infty} F_{\lambda} d\lambda\) is the total flux. Using \(F_{\text{AGN}} = L_{\text{AGN}}/4\pi r^2,\) the normalized spectrum of the AGN is assumed to be Nenkova et al. (2008),

\[
\lambda_{ds} \propto \begin{cases} \lambda^{1.2} \lambda \leq \lambda_{h} \\ \lambda^0 \lambda_{h} \leq \lambda \leq \lambda_{u} \\ \lambda^{-q} \lambda_{u} \leq \lambda \leq \lambda_{JR} \\ \lambda^{-3} \lambda_{JR} \leq \lambda \end{cases},
\]

where \(\lambda_{h} = 0.01\, \mu\text{m}, \lambda_{u} = 0.1\, \mu\text{m}, \lambda_{JR} = 1\, \mu\text{m},\) and \(q = 0.5.\) The estimated dust temperature at the inner radius is approximately \(T_{\text{ds}} \approx 1500\, \text{K},\) which is consistent with the sublimation temperature of the interior of a dust clump. The temperature of interior grain is given by (Chiang et al. 2001)

\[
T_{\text{d}}(r) = \left( \frac{L_{\text{AGN}}}{8\pi r^2 \sigma_{SB}} \sin \alpha \left[ 1 - e^{-\Sigma_d(k)_{\text{IR}}} \right] \right)^{1/4},
\]

where \(k\) is a size distribution averaged grain opacity. \(\langle k\rangle_{\text{IR}}\) is evaluated at the temperature of most luminous grains in the surface. We assume that the temperature of all grains at the midplane is thermally equilibrated.

Once the radial distributions of grain temperature at the surface and interior layer are obtained, the emission spectrum of the AGN torus can be calculated as below. The emission spectrum of the interior layer, \(F_{\lambda}^{i}\), is

\[
4\pi d^2 \lambda F_{\lambda}^{i} = 8\pi^2 \lambda \int_{r_{\alpha}}^{r_{\text{cut}}} B_{\lambda}(T_{\text{d}})(1 - e^{-\Sigma_d(k)_{\text{IR}}} r)dr,
\]

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\(^6\) http://home.strw.leidenuniv.nl/~moldata/

\(^7\) http://home.strw.leidenuniv.nl/~michiel/ratran/
where $d$ is the luminosity distance. The emission spectrum of the surface layer, $F^s_\lambda$, is

$$4\pi d^2\lambda F^s_\lambda = 8\pi^2\lambda \int_{r_a}^{r_m} (1 + e^{-\tau_s}) S_\lambda(1 - e^{-\tau_s}) \, dr,$$

where $S_\lambda$ and $\tau_s$ are the source function and optical depth given by (e.g., Chiang et al. 2001)

$$S_\lambda = \frac{2\int_{a_{\text{min}}}^{a_{\text{max}}} B_\lambda(T_{\text{clump}}) n(a) a^2 Q_{\text{abs}}(a, \lambda) da}{\int_{a_{\text{min}}}^{a_{\text{max}}} n(a) a^2 Q_{\text{abs}}(a, \lambda) da},$$

and

$$\tau_s = \frac{\int_{a_{\text{min}}}^{a_{\text{max}}} n(a) a^2 Q_{\text{abs}}(a, \lambda) da}{\int_{a_{\text{min}}}^{a_{\text{max}}} n(a) a^2 Q_{\text{abs}}/\text{AGN} \, da} \sin \alpha.$$

The dashed gray line in Figure 2 shows the SED for the equilibrium temperature structure of the dust torus.

### 3. Discussion

#### 3.1. Time Dependence of SED

The clump is optically thick in the shorter wavelength and optically thin in the longer wavelength than the mid-infrared emission domain. The dust clump at the midplane is heated by the near-infrared emission of the dust clump at the surface layer and reradiates its energy in mid- to far-infrared wavelengths. In the far-infrared wavelength, since a clump is optically thin, most of the photons emitted from the midplane escape without experiencing significant absorption. At the surface optically thin layer, clumps are sparsely distributed, and hence, the radiative interaction between clumps at the surface layer does not frequently occur. Based on the above considerations, we assume that the cooling timescale of the torus is mainly governed by that of each clump.

We calculate the time evolution of the torus SED after the central AGN is quenched. We assume that the temperature of the dust torus follows the characteristic cooling curve of the individual clump defined by Equations (20), (21), and (27). In addition, to take into account the light crossing time, the surface and midplane temperature at radius $r$ starts to decrease at $t = r/c$ and $t = 2r/c$ after the AGN is quenched, respectively. The factor of two in the latter is inserted so that the light crossing time of the vertical direction is taken into account as well as the radial direction. Since cooling timescale depends on the clump density, or the black hole mass, we derive the black hole mass by setting the initial AGN luminosity as 5% of the Eddington luminosity (e.g., Kelly et al. 2010).

Figure 2 shows the time dependence of the AGN torus SED with a face-on view after the quenching of the central engine with the initial AGN luminosity of $L_{\text{AGN}} = 10^{45}$ erg s$^{-1}$. Once the high-energy photons stop being emitted, individual clumps cool down rapidly, and the light crossing time of the torus, $t_{\text{cross}}/c \approx 30$ year, governs the cooling timescale. In Figure 3, we plot the change of mid-infrared 12 μm emission flux as a function of time since the central engine is quenched. The torus in higher luminosity AGNs shows a longer cooling time because of the larger torus outer radius as shown in Section 2.3.

#### 3.2. Searching for Dying AGN Candidates

To search for the dying AGN candidates discussed above, a longer and more stable timescale AGN indicator than the torus thermal emission is necessary to compare with the torus mid-infrared luminosity. NLR is a promising tool because its size is generally 10$^{2-4}$ pc, and the [O III]λ5007 emission line is one of the good NLR indicators hosting a strong luminosity correlation with AGN indicators (Ueda et al. 2015). A promising method is to cross-match optically selected type-2 AGNs obtained by the Sloan Digital Sky Survey (SDSS; York et al. 2000) with ALLWISE catalogs (Wright et al. 2010). SDSS type-2 AGNs have prominent [O III]λ5007 emission and ALLWISE will give us MIR 12 or 22 μm emission. Based on the luminosity relations of AGNs between [O III]λ5007 and 12 μm luminosity (Toba et al. 2014), log($L_{\text{O III}/\text{erg s}^{-1}}$) $\sim$ 44 is equivalent to log($L_{12\mu m}/\text{erg s}^{-1}$) $\sim$ 44, which is as luminous as QSO as shown with the gray dashed line in Figure 4. Using the time evolution function of 12 μm luminosity in Figure 3, we calculate the time evolution of the luminosity relation of [O III]λ5007 and 12 μm luminosity in Figure 4. The AGN located at the bottom right of Figure 4 would be a prominent candidate of those dying AGNs. This study could be achievable.
for type-2 AGNs with the redshift range of $z<0.3$, where the optical line diagnostics of AGNs can be applied (e.g., Kewley et al. 2006). Further studies using the method above will be discussed in a forthcoming paper (K. Ichikawa et al. 2017, in preparation).

The ongoing Subaru HSC (Miyazaki et al. 2012) SSP deep survey (Aihara et al. 2017a, 2017b), covering 28 deg$^2$, will also be a promising region for finding dying AGNs using [O iii] emitters at $z \sim 0.6$ and $\sim 0.8$ obtained with a narrow band filter NB816, NB921, respectively (Hayashi et al. 2017). Again, if there are sources with extremely low ratios of $L_{12,22} \mu$m$/L_{[O III]}$, this could be a prominent candidate of high-$z$ dying AGNs, which cannot be covered with the method of SDSS survey above. In this case, optical or near-infrared spectral follow-up is crucial to disentangle the [O iii] emitters into starburst galaxies and AGNs (e.g., Kewley et al. 2006).

4. Conclusions

The cooling time of the torus is mainly governed by the light crossing time of the torus from the central engine. The dust torus cools down by roughly one order of magnitude within 10 years once the propagation of the photon from the central engine stops, and the dust torus emission completely disappears within <100 years for most of the AGN luminosity range as shown in Figure 3. Those weak dust torus emissions or “dying” AGNs could be found with the combination of the optical spectral or narrow band survey detecting the NLR indicator [O iii]$\lambda$5007 by cross-matching with ALLWISE 12 or 22 $\mu$m band.

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