Mid-infrared Variability of Low-redshift Active Galactic Nuclei: Constraints on a Hot Dust Component with a Variable Covering Factor

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Abstract

We utilize mid-infrared multiepoch data from the Wide-field Infrared Survey Explorer over a ~10 yr period in the W1 (3.4 μm) and W2 (4.6 μm) bands to investigate the structure of dusty torus in low-redshift (0.15 < z < 0.4) active galactic nuclei (AGNs). We calculate a Spearman correlation coefficient (r12) between the W1 magnitude and W1 – W2 color based on the light curve in individual objects. Interestingly, r12 spans a broad range from −1 to 1 and is detected to be correlated with mean W1 – W2 color and AGN bolometric luminosity, in the sense that objects with a blue W1 – W2 color and low AGN luminosity tend to become redder (bluer) with increasing (decreasing) W1 brightness in the light curve (i.e., r12 < 0), although the correlation of r12 with the bolometric luminosity is relatively weak. The fit for the spectral energy distribution reveals a significant contribution from the host galaxy in the W1 and W2 bands. However, the dependencies of r12 on the W1 – W2 color and AGN luminosity still persist even after careful elimination of the host light contribution. We propose that this result can be explained if the covering factor of the hot dust component decreases as the AGN luminosity increases.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16)

1. Introduction

An accretion disk in the vicinity of a supermassive black hole and dense gas clouds, known as the broad-line region (BLR), is assumed to make up the central part of active galactic nuclei (AGNs), which is surrounded by a dusty torus. According to the unification model, the structures of type 1 and type 2 AGNs are identical but the AGN type is solely determined by the viewing angle to the opening angle of the dusty torus (Antonucci 1993; Urry & Padovani 1995). In this regard, it is critical to understand the detailed structure of the torus to examine the AGN unification model.

While clumpy dust instead of smooth dust may mimic the geometrical structure of the torus (e.g., Pier & Krolik 1992; Fritz et al. 2006; Nenkova et al. 2008; Hönig & Kishimoto 2010; Stalevski et al. 2016), several critical concerns about the torus structure remain unresolved. For example, the covering factor of the torus is one of the most essential parameters to determine the torus structure. Various observational studies reached somewhat different conclusions. Some studies claimed that the covering factor is somewhat linked with the Eddington ratio (e.g., Ezhilkone et al. 2017; Ricci et al. 2017; Zhuang et al. 2018) and independent of AGN luminosity (e.g., Hao et al. 2010, 2011; Mor & Netzer 2012; Netzer et al. 2016). However, using the ratio of mid-infrared luminosity and AGN bolometric luminosity, various other studies demonstrated that the covering factor is anticorrelated with AGN luminosity (e.g., Maiolino et al. 2007; Mor & Trakhtenbrot 2011; Lusso et al. 2013; Roseboom et al. 2013), favoring a receding torus model (Lawrence 1991; Simpson 2005; Hönig & Beckert 2007).

The spectral energy distribution (SED) of the near-infrared (NIR) and mid-infrared (MIR) is critical to constrain the physical properties of the dusty torus as the dust heated by the immense energy from the accretion disk reradiates thermal emission in the infrared (IR). It is well known that the IR SED can be represented by hot and warm components (e.g., Barvains 1987; Suganuma et al. 2006; Mor & Netzer 2012), although an additional contribution from polar dust may not be insignificant (e.g., Hönig et al. 2013; Lyu & Rieke 2018; Mountrichas et al. 2020; Yang et al. 2020; Buat et al. 2021; Toba et al. 2021). Several observational studies discovered a population of AGNs lacking the hot dust component at moderate and high redshifts, based on the IR SED of the AGNs (e.g., Jiang et al. 2010; Hao et al. 2010, 2011). In addition, Hao et al. (2011) claimed that the fraction of hot-dust-deficient (HDD) AGNs in the distant universe is greater than that in the local universe. However, other studies demonstrated that the population of HDD AGNs may not be correlated with the redshift but firmly connected to the physical properties of AGNs, such as bolometric luminosity and Eddington ratio (e.g., Mor & Netzer 2012; Jun & Im 2013; Lyu et al. 2017).

Despite various previous studies, it is still vital to understand the structure of the dusty torus and how it relates to the physical properties of AGNs. In this study, we utilize an independent approach based on the characteristics of MIR variability to investigate the physical properties of the dusty torus. The sample selection and multiepoch data are presented in Section 2. We describe the approach to quantify the characteristics of MIR variability in Section 3. In Section 4, we discuss the physical origin of our findings. Throughout the study, we assume a cosmology with $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Sample and Data

2.1. Sample

Our sample is drawn from the Sloan Digital Sky Survey (SDSS). We select type 1 and type 2 AGNs from the SDSS Data Release 14 (DR14) quasar catalog (Pâris et al. 2018) and...
the SDSS Max Planck Institute for Astrophysics-Johns Hopkins University (MPA-JHU) Data Release 8 (DR8) catalog (Kauffmann et al. 2003; Brinchmann et al. 2004), respectively. Because the MPA-JHU catalog contains all types of galaxies, we utilized only galaxies classified as AGNs according to the Baldwin–Phillips–Terlevich (BPT) diagram (Baldwin et al. 1981) in MPA-JHU classifications (BPTCLASS = 4; Brinchmann et al. 2004). For both types of AGNs, we impose a minimum redshift of 0.15 to minimize the host galaxy contamination from extended features in the W1 (3.4 μm) and W2 (4.6 μm) bands and a maximum redshift of 0.4 to ensure that Hα is covered by the SDSS spectrum for the AGN classification using the BPT diagram. For type 2 AGNs, 402 duplicates were removed from the MPA-JHU catalog. We find that 922 type 2 AGNs initially selected from the MPA-JHU catalog are also classified type 1 in the SDSS QSO catalog; they are regarded as type 1 in this study, yielding an initial sample of 7443 type 1 and 5531 type 2 AGNs.

To investigate the MIR variability of SDSS-selected AGNs, we employed photometric data of the W1 and W2 bands from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). Multiepoch data are retrieved from the AllWISE Multiepoch Photometry Table and the NEOWISE-R Single Exposure (L1b) Source Table at the NASA/IPAC Infrared Science Archive (IRSA; https://irsa.ipac.caltech.edu/) with a matching radius of 2″. Sources with detection in the W1 band typically have astrometric uncertainties of less than 0.05′′, indicating the matching radius is sufficient to capture the IR counterpart (see also Assef et al. 2013). Among the initial sample, 7368 type 1 and 5491 type 2 AGNs were detected by WISE or NEOWISE. WISE visited a particular field in the sky every six months and typically observed that field 14 times for three days in each visit. As a result, we bin the photometric data into \( \sim \pm 15 \) days to obtain a representative magnitude in each visit. To remove poor-quality data, only the photometry flagged with \( cc_{\text{flags}} = 0 \), \( qual_{\text{frame}} > 0 \), \( qi_{\text{fact}} > 0 \), \( saa_{\text{sep}} > 0 \), and \( moon_{\text{masked}} = 0 \) were averaged after 3σ clipping in a single visit (Figure 1). Following Lyu et al. (2019), we evaluated the magnitude uncertainty for each epoch as follows:

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\sigma_{\text{epoch}} = \frac{1}{N - 1} \sum_{i=1}^{N} (m_i - \bar{m}_{\text{epoch}})^2 + \frac{1}{N} \sum_{i, \text{pho}} \sigma_{\text{pho}}^2 + \frac{1}{N} \sigma_{\text{s.s.}}^2,
\]

where \( m_i \) and \( \sigma_{\text{pho}} \) denote the magnitude and its uncertainty at each observation, respectively, in the Vega magnitude system; \( \bar{m}_{\text{epoch}} \) denotes the mean magnitude at each epoch; and \( \sigma_{\text{s.s.}} \) denotes the system stability (~0.029 and ~0.016 mag for WISE and NEOWISE, respectively). The light curve typically spans a baseline of 10 yr with a cadence of 6 months. Note that there is a ~40 month gap between WISE and NEOWISE.

![Figure 1](https://wise2.ipac.caltech.edu/docs/release/allwise/expsup) An example of a light curve. Blue and red represent the light curves after binning for the W1 and W2 bands, respectively, while gray denotes the original measurements before binning.

2.2. MIR Variability

To identify variable objects, we utilize the \( \chi^2 \) of the light curve: \( \chi^2 = \sum_{i=1}^{N} \left( \frac{m_i - \bar{m}}{\sigma_i} \right)^2 \), where \( \bar{m} \) represents the mean magnitude over the entire epochs and \( \sigma_i \) is the uncertainty in each epoch. Following the recipe in Sánchez et al. (2017), we defined \( P_{\text{var}} = 1 - P(\chi^2) \), where \( P(\chi^2) \) is the probability that the computed \( \chi^2 \) or lower value can be obtained by chance from an invariable source (see also McLaughlin et al. 1996). Therefore, a low \( P(\chi^2) \) (high \( P_{\text{var}} \)) implies that the object is likely to be variable. We classified it as a variable object if \( P_{\text{var}} > 0.95 \) both for W1 and W2 (Lanzuisi et al. 2014; Cartier et al. 2015; Sánchez et al. 2017; Kim et al. 2018). Note that we utilized a sample with a sufficiently large number of epochs (\( N_{\text{epoch}} \geq 10 \)). Due to the larger uncertainty in W2 compared to W1 as shown in Figure 1, the main reason for the rejection is the relatively smaller \( P_{\text{var}} \) in the W2 band. Finally, a total of 2114 type 1 AGNs and 623 type 2 AGNs were identified as variable sources. We conducted further investigation into these sources.

2.3. AGN Properties

We estimated the bolometric luminosity \( L_{\text{bol}} \) using the [O III] \( \lambda 5007 \) luminosity by adopting a conversion of \( L_{\text{bol}}/L_{\text{O III}} \approx 3500 \) (Heckman et al. 2004). Note that the conversion factor can be significantly smaller or dependent on the AGN luminosity for the extinction corrected for [O III] luminosity (Kauffmann & Heckman 2009; Trump et al. 2015; Kong & Ho 2018). However, because our goal is to examine the trend of MIR variability as a function of \( L_{\text{bol}} \) adopting a single universal bolometric correction from Heckman et al. (2004) is sufficient for that purpose.
The [O III] luminosity of type 1 and type 2 AGNs was taken from Rakshit et al. (2020) and the MPA-JHU DR8 catalog, respectively. The distributions of the bolometric luminosity and redshift of the sample are shown in Figure 2. Note that there is a clear difference between the type 1 and type 2 subsamples, in the sense that type 1 AGNs have greater bolometric luminosity and larger redshift compared to type 2 AGNs. Despite this genuine difference, the two samples show similar trends in the characteristics of MIR variability as shown in Section 3. It reveals that the main result of this study is not dependent on this bias.

For type 1 AGNs, black hole (BH) mass is calculated using the virial method, in which the BH mass \( M_{\text{BH}} \sim R V^2 / G \) can be inferred from the size \( R \) and velocity dispersion \( V \) of the BLR underneath the central BH. Thanks to the tight correlation between \( R \) and AGN luminosity \( L \) relation, one can estimate the BH mass using a single-epoch spectrum. However, in virial mass estimates, there is an unknown scaling factor \( f \), which is sensitive to the geometry and kinematics of the gas clouds in the BLR. In general, \( f \) is determined by assuming that host galaxies of AGNs follow the same \( M_{\text{BH}} - \sigma \) relation of normal galaxies (e.g., Onken et al. 2004; Woo et al. 2013). As a result, a single universal scaling factor is used to estimate the BH mass, although it can depend on the physical properties of AGNs (e.g., Marconi et al. 2008). Therefore, in addition to the intrinsic scatter in the \( R-L \) relation, the unknown scaling factor can naturally introduce an uncertainty \((\sim 0.5 \text{ dex}) \) in the BH mass derived from the virial method (e.g., Park et al. 2012).

The line width (FWHM) and flux of broad emissions (H\( \beta \) and H\( \alpha \)) were taken from Rakshit et al. (2020), whose values are measured from the decomposition of SDSS spectra. The broad emission lines were fitted with multiple-Gaussian models. We adopted a calibration of the BH mass estimator from Ho & Kim (2015) based on the H\( \beta \) and 5100 \( \AA \) AGN continuum luminosity (Kim et al. 2021a). We primarily utilized

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\text{H}\alpha \text{ line widths and H}\alpha \text{ luminosity as } \text{H}\alpha \text{ is minimally influenced by the complex Fe II multiplets than H}\beta. \text{ For the conversions of line luminosity to } 5100 \text{ } \AA \text{ AGN luminosity, and H}\alpha \text{ line widths to H}\beta \text{ line widths, we employed the relations of Greene & Ho (2005). For those without reliable spectral measurements for H}\alpha, \text{ we utilized H}\beta \text{ instead. Overall, the BH mass can be calculated from the virial method for 2112 out of 2114 type 1 AGNs.}
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For type 2 AGNs, the BH mass was computed from the total stellar mass of the host galaxy using the \( M_{\text{BH}} - M_* \) relation. We adopted the \( M_{\text{BH}} - M_* \) relation from Greene et al. (2020) for all morphological types of galaxies. Note that the uncertainty of this BH mass estimate \((\sim 0.8 \text{ dex}) \) is significantly greater than that \((\sim 0.5 \text{ dex}) \) of the virial method due to the intrinsic scatter in the \( M_{\text{BH}} - M_* \) relation (Greene et al. 2020). The stellar mass, derived from the SED fit for the photometric data of \( ugriz \), was taken from the MPA-JHU catalog for 613 out of 623 type 2 AGNs. Figure 3 shows the distributions of the BH mass and Eddington ratio of the variable sources, in which there is little difference between type 1 and type 2 AGNs, contrary to the distributions of bolometric luminosity and redshift.

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\text{3. Result}
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3.1. \text{The Connection between MIR Variability and AGN Properties}
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In order to quantify the characteristics of MIR variability of an individual AGN from the light curve, we utilized the Spearman correlation coefficient between W1 (mag) and the W1 – W2 color (hereafter \( r_{12} \)). If the W1 – W2 color decreases (i.e., bluer in color) with increasing AGN brightness in the light curve, \( r_{12} \) is predicted to be positive (Figure 4). However, if the MIR color becomes redder as the AGN brightness increases, \( r_{12} \) is predicted to be negative. Surprisingly, \( r_{12} \) is found to have a broad distribution from -1 to 1, indicating the structure of the torus may be complicated and different between AGNs, possibly dependent
on AGN properties. To investigate the physical origin of the wide spread of $r_{12}$, we performed a comparison of $r_{12}$ with various physical properties. We found that $r_{12}$ is moderately correlated with the W1 − W2 color ($r_s = 0.45$ and 0.59 for type 1 and type 2, respectively) and mildly correlated with the bolometric luminosity ($r_s = 0.28$ and 0.32 for type 1 and type 2, respectively; Figures 5 and 6). $P$-values are smaller than 0.001 in both cases, implying that the null hypothesis (no correlation) can be rejected. However, $r_{12}$ appears to be weakly or not correlated with the Eddington ratio (Figure 7 and Table 1).

The rest-frame central wavelengths of W1 and W2 vary with the redshift and hence the light contamination from the host and accretion disk can also vary with the redshift. In addition, the distributions of bolometric luminosity and redshift are clearly different between type 1 and type 2 AGNs. To minimize those biases, we divide our sample into three subsamples according to their redshift. Our finding that $r_{12}$ is correlated with the W1 − W2 color and bolometric luminosity is the same regardless of the redshift (Figures 5 and 6). At $0.2 < z < 0.3$, where the difference between type 1 and type 2 AGNs in the distribution of bolometric luminosity is minimized, the trend is almost identical for both AGN types. It may reveal that the overall trend may not be affected by the bias in the distribution of bolometric luminosity.

Interestingly, the distributions of $r_{12}$ are distinguishable between type 1 and type 2 AGNs, in the sense that the mean $r_{12}$ of type 2 ($\sim -0.13 \pm 0.46$) is systematically smaller than that of type 1 ($\sim 0.33 \pm 0.42$). This may be partly due to the fact that
type 1 tends to have larger bolometric luminosity and redder \( W_1 - W_2 \) color compared to type 2. This may be due to the fact that SDSS spectroscopic data were obtained for a flux-limited sample \((r < 17.77)\). Therefore, for type 2 objects, the sample is biased toward AGNs with more-luminous hosts, leading to bluer \( W_1 - W_2 \) color. On the contrary, type 1 sources, owing to the light contribution from the AGN itself in the optical band, can be relatively free of this bias. While AGNs tend to have red color in \( W_1 - W_2 \) \( (i.e., W_1 - W_2 > 0.8; \text{Stern et al. 2012}) \), a large fraction of type 2 AGNs appear to have \( W_1 - W_2 \) less than 0.8, which again suggests the substantial contribution from the host in these objects. We will discuss this in more detail in Section 4.1. However, the correlation coefficient between \( r_{12} \) and \( W_1 - W_2 \) color appeared to be systematically greater for type 2 than type 1 (0.59 versus 0.45), possibly implying that the genuine torus structure or the viewing angles of type 1 and type 2 AGNs are not identical. Because, however, it is not only that the AGN properties of the sample \( (e.g., \text{bolometric luminosity}) \) are variable between type 1 and type 2, but the host contamination is also nonnegligible in MIR, these indicate the need for those factors to be fully taken into account to investigate the physical origin of our findings \( (\text{see Section 4.1}) \).

3.2. Composite Spectra

To investigate the origin of the observed dependence of \( r_{12} \) on \( L_{\text{bol}} \), we constructed NIR/MIR composite spectra by

![Figure 5](image-url)
employing the photometric data from 2MASS \((JHK_s;\) Skrutskie et al. 2006) and WISE \((W1, W2, W3, \text{and } W4)\). We used a matching radius of 2″ for the cross-correlation of WISE with 2MASS. Note that the optical data are excluded because the light contribution from the accretion disk is severe at short wavelengths, which makes a direct comparison between the two AGN types difficult. Following the method of Hickox et al. (2017), we included objects detected in all seven bands \((1866 \text{ type 1 and 559 type 2 AGNs})\). For each object, the photometric data were converted to the rest frame, and fluxes in wavelengths ranging from 1–17 μm are calculated by interpolating the photometric data in log–log space. The interpolated spectrum of each object is normalized to the integrated flux within 8–13 μm. The composite spectrum is established by averaging the fluxes from all sources in each spectral bin. To prevent the systematic bias owing to outliers, we exclude fluxes using iterations of 3σ clipping. We divide the sample into six subsamples based on AGN type and \(L_{\text{bol}}\) to investigate how the SED shape depends on those parameters (Figure 8). Overall, 252, 785, and 829 type 1 objects \((321, 171, \text{and 67 type 2 objects})\) were employed to generate the composite spectra for low-luminosity \((\log L_{\text{bol}} \lesssim 45 \text{ erg s}^{-1})\), moderate-luminosity \((45 < \log L_{\text{bol}} \lesssim 46 \text{ erg s}^{-1})\), and high-luminosity objects \((\log L_{\text{bol}} > 46 \text{ erg s}^{-1})\), respectively. In both types of AGNs, more-luminous AGNs tend to have redder MIR color compared to less-luminous AGNs. In addition, the

Figure 6. Dependence of \(r_{12}\) on \(W_1 - W_2\) for (a) the entire sample, (b) objects with \(0.15 < z \leq 0.2\), (c) objects with \(0.2 < z \leq 0.3\), and (d) objects with \(0.3 < z \leq 0.4\). The symbols are the same as in Figure 4.
signature of the host galaxy light in the NIR appeared to stand out more in type 2 AGNs. This is likely because type 2 AGN are systematically biased toward having greater NIR emission from the host galaxy owing to the shallowness of the 2MASS survey. It demonstrates the importance of quantifying the host contribution to understand the characteristics of MIR variability.

4. Discussions

4.1. Host Contamination

We found that $r_{12}$ is strongly correlated with the W1 – W2 color and bolometric luminosity. Objects with a bluer MIR color or lower luminosity tend to have smaller $r_{12}$ than those with a redder MIR color or higher luminosity. Taken at face value, this may indicate that the structure of the dusty torus is directly dependent upon the bolometric luminosity and subsequently the MIR color. However, this trend can be naturally explained if the MIR light is dominated by the host component. In contrast to the AGN light, the stellar light is intrinsically blue in MIR and does not vary on a timescale of years. As a result, if the AGN outshines the host light in the low-luminosity and host-dominated AGN, the MIR becomes brighter and redder (i.e., $r_{12} < 0$). Therefore, it is crucial to robustly take the host contribution into account. Here, we utilized two different methods to estimate the relative host

Figure 7. Dependence of $r_{12}$ on Eddington ratio for (a) the entire sample, (b) objects with $0.15 < z \leq 0.2$, (c) objects with $0.2 < z \leq 0.3$, and (d) objects with $0.3 < z \leq 0.4$. The symbols are the same as in Figure 4.
Figure 8. Composite spectra of (a) type 1 AGNs and (b) type 2 AGNs. In each panel, we divide the sample according to the bolometric luminosity: \( \log L_{\text{bol}} / \text{erg s}^{-1} \leq 45 \) (black line), \( 45 < \log L_{\text{bol}} / \text{erg s}^{-1} < 45 \) (blue dashed line), and \( 45 < \log L_{\text{bol}} / \text{erg s}^{-1} \leq 46 \) (red dotted line). The shaded regions represent the 1\( \sigma \) dispersions of the composite spectra.

Table 1

| Parameter            | Sample   | Type 1         | Type 2         | Type 1 (Cor.) | Type 2 (Cor.) |
|----------------------|----------|----------------|----------------|---------------|---------------|
|                      |          | \( r_s \) | \( p \)-value | \( r_s \) | \( p \)-value | \( r_s \) | \( p \)-value | \( r_s \) | \( p \)-value |
| \( W1 - W2 \)        | All      | 0.45         | <0.001        | 0.59         | <0.001        | 0.24         | <0.001        | 0.64         | <0.001        |
| \( 0.15 < z \leq 0.2 \) | All      | 0.48         | <0.001        | 0.53         | <0.001        | 0.11         | 0.135         | 0.63         | <0.001        |
| \( 0.2 < z \leq 0.3 \) | All      | 0.52         | <0.001        | 0.68         | <0.001        | 0.30         | <0.001        | 0.67         | <0.001        |
| \( 0.3 < z \leq 0.4 \) | All      | 0.42         | <0.001        | 0.67         | <0.001        | 0.22         | <0.001        | 0.36         | 0.427         |

| \( \log L_{\text{bol}} \) | All      | 0.28         | <0.001        | 0.32         | <0.001        | 0.19         | <0.001        | 0.32         | <0.001        |
| \( 0.15 < z \leq 0.2 \) | All      | 0.31         | <0.001        | 0.30         | <0.001        | 0.22         | 0.003         | 0.39         | <0.001        |
| \( 0.2 < z \leq 0.3 \) | All      | 0.32         | <0.001        | 0.32         | <0.001        | 0.29         | <0.001        | 0.27         | 0.002         |
| \( 0.3 < z \leq 0.4 \) | All      | 0.30         | <0.001        | 0.43         | 0.034         | 0.26         | <0.001        | 0.72         | 0.068         |

| \( \log(L_{\text{bol}}/L_{\text{bol}}) \) | All      | 0.20         | <0.001        | 0.12         | 0.002         | 0.13         | <0.001        | 0.25         | <0.001        |
| \( 0.15 < z \leq 0.2 \) | All      | 0.25         | <0.001        | 0.03         | 0.552         | 0.10         | 0.166         | 0.23         | 0.002         |
| \( 0.2 < z \leq 0.3 \) | All      | 0.19         | <0.001        | 0.27         | <0.001        | 0.15         | <0.001        | 0.26         | 0.003         |
| \( 0.3 < z \leq 0.4 \) | All      | 0.19         | <0.001        | 0.02         | 0.943         | 0.11         | 0.009         | 0.65         | 0.111         |

Notes. Col. (1): Physical parameter. Col. (2): Sample. Col. (3): Spearman correlation coefficient for type 1 AGNs. Col. (4): Probability value that the correlation occurs by chance for type 1 AGNs. Col. (5): Spearman correlation coefficient for type 2 AGNs. Col. (6): Probability value that the correlation occurs by chance for type 2 AGNs. Col. (7): Spearman correlation coefficient for type 1 AGNs after the correction for the host contribution. Col. (8): Probability value that the correlation occurs by chance for type 1 AGNs after the correction for the host contribution. Col. (9): Spearman correlation coefficient for type 2 AGNs after the correction for the host contribution. Col. (10): Probability value that the correlation occurs by chance for type 2 AGNs after the correction for the host contribution.

The mass-to-light ratio of passive galaxies (~0.2) at the W1 band was adopted from Kettlety et al. (2018), as the MIR SED of the AGN host is established to be well fit with that of early-type galaxies (Hickox et al. 2017). In this method, the result needs to be interpreted with caution.

Second, to robustly remove the light contamination from the host, we applied the SED fit to the broadband photometry of each object. For the SED fit, we utilized photometric data from
2MASS (JHK$_s$) and WISE (W1 and W2 bands). Because the SED fit with the W3 and W4 bands often leads to unsatisfactory results, those were excluded in this experiment. As the W1 and W2 fluxes were measured through the PSF photometry, it can miss the flux from extended structures if present. Therefore, to keep the consistency between the photometric data, we only utilized the objects in the 2MASS present. Therefore, to keep the consistency between the photometry, it can miss the flux from extended structures if present. Therefore, to keep the consistency between the photometric data, we only utilized the objects in the 2MASS point-source catalog (PSC). We employed the template spectra for AGNs and for an elliptical, spiral, and irregular galaxy from Assef et al. (2010). A broad range of galaxy types provides better coverage of the diverse stellar population expected for the host galaxies of type 1 and type 2 AGNs (e.g., Kim & Ho 2019; Zhao et al. 2019, 2021). During the fit, the extinction for the AGN template is considered by varying $A_V$. From the SED fit, we computed the light contributions from the host in the W1 and W2 bands and subtract those from photometric data in every epoch (Figure 10). Finally, we recalculate $r_{12}$ using the host-subtracted magnitudes in the W1 and W2 bands.

Figure 11 (Figure 12) shows the correlations between $r_{12}$ and W1 – W2 color (bolometric luminosity) before and after the subtraction of host light. The fractions of host light in W1 were, on average, 22% and 39% in type 1 and type 2 AGNs, respectively. This is in broad agreement with the results from the stellar mass for type 2 AGNs. However, the SED fit yielded a slightly larger host fraction in W1, possibly because both methods used templates from different types of host galaxies. The host light subtraction naturally resulted in a marginal increase in W1 – W2 color ($\sim0.1$–0.2) and a more substantial increase in $r_{12}$ ($\sim0.19$–0.38 on average). Figure 11 clearly shows that, after the correction, the majority of the sample have W1 – W2 color larger than 0.8 mag, which is consistent with the previous criterion for AGN selection (e.g., Stern et al. 2012). As a result, the level of dependence of $r_{12}$ on W1 – W2 color became slightly lower only for type 1. Before the host correction, $r_s \sim 0.40$ for type 1 and 0.63 for type 2, in comparison with $r_s \sim 0.24$ for type 1 and 0.64 for type 2 after the correction. However, the general trend, in which $r_{12}$ tends to decrease with decreasing W1 – W2, remains the same. This experiment reveals that the dependency on W1–W2 is not entirely due to the host contamination, rather it is more likely connected with the intrinsic properties of the dusty torus. Similarly, the trend for the dependence of $r_{12}$ on AGN luminosity also still remains the same after the correction for the host galaxy. The correlation coefficients between $r_{12}$ and the physical parameters of AGNs after the correction for the host galaxy are listed in Table 1.

4.2. Physical Origin for the Wide Range of $r_{12}$

The brightness and color in W1 and W2 can be determined from several physical parameters, such as extinction for the AGN ($A_V$), the existence and covering factor of a hot dust component, viewing angle, and host galaxy contamination (e.g., Nenkova et al. 2008; Stalevski et al. 2016; Hickox et al. 2017; Lyu et al. 2017). Our findings imply that the characteristics of variability in W1 and W2 are strongly dependent upon W1 – W2 color and AGN luminosity. In Section 4.1, we demonstrate that the host contamination cannot be a physical origin of such trends. In addition, the viewing angle may not change dramatically in a single object. Therefore, we conclude that the hot dust component or the obscuration may be the main driver of the variability of the W1 – W2 color.

4.2.1. What Makes $r_{12}$ Positive?

The innermost radius of the torus is determined by the sublimation of the dust (Barvainis 1987; Suganuma et al. 2006). Therefore, it is well known that a hotter dust component has a smaller sublimation radius than a warmer dust component, indicating that dust emission from shorter wavelengths originates from an inner part of the torus (Koshida et al. 2018; Lyu et al. 2019). Therefore, the reprocessed emission in W1 responded to the variation of the continuum from the accretion disk more quickly than that in W2. As a result, the W1 – W2 color became blue (red) with increasing (decreasing) AGN luminosity, yielding a positive $r_{12}$ unless there is no change in the structure of the torus. To confirm this hypothesis, we estimate the time lag between W1 and W2 based on the light curve by employing interpolated cross-correlation functions (ICCF; Peterson et al. 1998; Sun et al. 2018). We consider the centroid of the ICCF as the time lag. Errors on the time lags were estimated from Monte Carlo (MC) iterations (Gaskell & Peterson 1987). Figure 13 shows that the time lag is greater than zero, revealing that W1 emission radiates from the inner part of the torus compared to W2. We also find that the time lag is correlated with $L_{bol}$, although with a large scatter, which is in broad agreement with the results from previous studies (Lyu et al. 2019). The correlation appears to be very weak due to the sparse sampling (∼6 months) of the WISE light curves.

4.2.2. Viewing Angle and Obscuration

The level of dependence of the W1 – W2 color and $L_{bol}$ on $r_{12}$ is greater for type 2 than for type 1 AGNs, irrespective of whether the host contamination is taken into account. This is partially owing to the fact that type 1 AGNs lack objects with $r_{12} < 0$. Therefore, it may indicate either the contribution from
the accretion disk is not negligible even in W1 or the genuine structures of the dusty torus between type 1 and type 2 AGNs may vary. The viewing angle and obscuration may also play an important role in shaping the NIR/MIR SED, in the sense that the smaller viewing angle and lower extinction can result in the bluer color in W1 and W2 (e.g., Nenkova et al. 2008; Stalevski et al. 2016). In this light, a marginal difference in $r_{12}$ distributions between type 1 and type 2 AGNs can be described by those parameters.

According to the AGN unification model, type 1 AGNs are expected to have a smaller viewing angle and less obscuration than type 2 AGNs. As a result, if the extinction and viewing angle are predominantly responsible for the W1 − W2 color, type 1 AGNs ought to have a bluer W1 − W2 color than type 2 AGNs, which is inconsistent with our finding that type 2 AGNs have a slightly bluer W1 − W2 color than type 1 AGNs. In addition, Figure 14 demonstrates that higher-luminosity AGNs tend to have a redder color, which is also contrary to the fact that the obscured AGN fraction decreases with the AGN luminosity (e.g., Maiolino et al. 2007; Lusso et al. 2013), if the red color is due to the high obscuration. It implies that neither obscuration nor
viewing angle plays a primary role in determining the W1 – W2 color.

4.2.3. Covering Factor of the Hot Dust Component

It is known that the NIR/MIR SED of AGN is well fit with two components: a hot graphite dust component that peaks around 2–3 μm (Richards et al. 2006; Netzer et al. 2007; Mor & Netzer 2012) and a warm silicate-type dust component (e.g., Nenkova et al. 2008). Furthermore, the brightness in W1 and W2 is dominated by the emission from the hot dust component (Mor & Trakhtenbrot 2011). Therefore, the variability and SED shape are likely sensitive to the physical properties of the hot component. Mor & Trakhtenbrot (2011) demonstrated that the covering factor of the hot dust component is anticorrelated with the AGN bolometric luminosity ($L_{\text{bol}}$). This is consistent with our finding that less-luminous AGNs have bluer W1 – W2 owing to the greater contribution from the hot dust component (Figure 13). This can be also confirmed from the composite spectra, in the sense that

*Figure 12.* Correlations between $r_{12}$ and AGN bolometric luminosity (a) before and (b) after the subtraction of host light. The symbols and lines are the same as for Figure 6.

*Figure 13.* Distributions of time lag between W1 and W2 as a function of bolometric luminosity. Type 1 and type 2 objects are denoted by open blue circles and red stars, respectively. The fitting results of linear regression are shown by the blue solid line and red dashed line for type 1 and type 2 objects, respectively. The thick gray line represents the relation inferred from Lyu et al. (2019).

*Figure 14.* Relationship between W1 – W2 color and AGN bolometric luminosity. The symbols and lines are the same as in Figure 13. The W1 – W2 color is corrected for the host galaxy contribution.

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The W1 luminosity sanity check, we compared the AGN bolometric luminosity and corrected for the host contribution. The W1 luminosity is dotted line denotes the one-to-one correspondence. The W1 luminosity is corrected for the host contribution.

low-luminosity AGNs tend to have bluer color in 1–5 μm. As a sanity check, we compared the AGN bolometric luminosity and the W1 luminosity \( L_{W1} \), which were calculated in the rest frame. \( k \)-correction was computed using the observed W1 – W2 color. We found that the slopes between \( L_{bol} \) and \( L_{W1} \) (-0.76 and 0.63 for type 1 and type 2, respectively) were smaller than 1 before taking the host contribution into account. However, after the subtraction of the host light, the slopes became 0.92 and 0.91 for type 1 and type 2, respectively (Figure 15). This finding is in broad agreement with previous observational studies (Lusso et al. 2013), indicating that the covering factor of the hot dust decreases as the AGN luminosity increases. Furthermore, there is a marginal discrepancy between type 1 and type 2 AGNs in this correlation. This result likely supports the scenario of the clumpy torus in which the hot component is less obscured than in the smooth torus model.

In addition, the sublimation radius \( R_{sub} \) of the hot dust component is correlated with \( L_{bol} \), given by

\[
R_{sub} \approx 0.5 \left( \frac{L_{bol}}{10^{46.5} \text{erg s}^{-1}} \right)^{0.5} \left( \frac{1800 K}{T_{sub}} \right)^{2.8} \text{pc},
\]

where \( T_{sub} \) denotes a sublimation temperature of pure-graphite grains (Mor & Netzer 2012). Therefore, low-luminosity AGNs tend to have a smaller innermost radius compared to high-luminosity AGNs. One of the most interesting findings in our study is that for low-luminosity AGNs with blue W1 – W2, the W1 – W2 color becomes redder with increasing AGN luminosity in the light curve (i.e., \( r_{12} < 0 \)). This may indicate that the hot dust at the innermost radius can be easily evaporated by the enhanced emission from the accretion disk. Interestingly, Yang et al. (2018) reported that changing-look (CL) AGNs also tend to have \( r_{12} < 0 \). This may imply that the CL AGN event occurs due to the change in the accretion rate.

Lyu et al. (2019) evaluated the radii \( (R_{W1} \) and \( R_{W2} \) of the torus inferred from the time lag between the optical UV/optical emission and reprocessed emission in the W1 and W2 bands, respectively (Equations (15) and (16) of Lyu et al. 2019). They claimed that the torus size is strongly correlated with the AGN bolometric luminosity (see also Glass 2004; Koshida et al. 2014). Figure 16 shows the comparison between the sublimation radius and the torus radii. \( R_{sub} \) is almost identical to \( R_{W1} \) and significantly smaller than \( R_{W2} \), implying that dust material emitting in the W1 band can be vulnerable to sublimation. It confirms that our argument is relevant.

However, for high-luminosity AGNs with red W1 – W2, the covering factor of the hot dust component can be reduced. Therefore, the NIR/MIR SED is unlikely sensitive to the evaporation of the hot dust and more likely determined by the warm dust component. In Figure 16, at \( L_{bol} \geq 10^{45.5} \text{erg s}^{-1} \), \( R_{W1} \) becomes smaller than \( R_{sub} \), revealing that the hot graphite dust may have evaporated already.

Finally, polar dust has been found in high-resolution MIR images of nearby type 1 AGNs (e.g., Höning et al. 2013; Stalevski et al. 2017). In addition, the light contribution from the polar dust may be substantial in the MIR SED (e.g., Lyu & Rieke 2018; Yang et al. 2020; Toba et al. 2021). Therefore, one might suspect whether the polar dust can be responsible for the trend found in this study. However, the location of the polar dust (i.e., close to the sublimation radius or located in the host galaxies) is still under debate (e.g., Lyu & Rieke 2018; Yang et al. 2020). Moreover, the physical properties of the polar dust in type 2 AGNs are unknown. Therefore, investigating the contribution from the polar dust is beyond the scope of our study.
5. Summary

Using the light curves in the W1 and W2 bands generated from WISE multiepoch data, we found that the W1 – W2 color varies in response to the light variation of AGNs. This indicates that the structure of the dusty torus is sensitive to AGN luminosity. Furthermore, the trend of the color variation greatly depends on the MIR color and AGN bolometric luminosity, in the sense that low-luminosity (high-luminosity) AGNs with blue (red) W1 – W2 color tend to turn redder (bluer) in W1 – W2 color with increasing IR luminosity. We found such a trend is still valid, even after taking the host contribution in NIR/MIR into account, suggesting the host light is not the predominant reason for the color variation. We argue that the anticorrelation between the covering factor of the hot dust component and AGN luminosity can be the major reason for our findings, which is consistent with previous studies. Our results demonstrate that the color variation in NIR/MIR inferred from the multiepoch data can serve as a powerful tool to investigate the detailed structure of the torus. For example, the SPHEREx mission will obtain multiepoch spectral images in ~200 deg² of deep fields with a 2 yr lifetime mission (Doré et al. 2018; Kim et al. 2021b). The multiepoch spectral data covering 0.75–5.00 μm will provide a unique opportunity to address this subject in depth.

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