Dust Reverberation of 3C 273: Torus Structure and Lag–Luminosity Relation

Catalina Sobrino Figaredo1, Martin Haas1, Michael Ramolla1, Rolf Chini1,2, Julia Blex1, Klaus Werner Hodapp3, Miguel Murphy2, Wolfram Kollatschny4, Doron Chelouche5, and Shai Kaspi6

1 Astronomisches Institut Ruhr-Universität Bochum, Universitätsstr. 150, D-44801 Bochum, Germany
2 Universidad Católica del Norte, Antofagasta, Chile
3 Institute for Astronomy, 640 North A‘ohoku Place, Hilo, HI 96720-2700, USA
4 Institut für Astrophysik, Universität Göttingen, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany
5 Physics Department and the Haifa Research Center for Theoretical Physics and Astrophysics, University of Haifa, Israel
6 School of Physics & Astronomy and the Wise Observatory, The Raymond and Beverly Sackler Faculty of Exact Sciences Tel-Aviv University, Israel

Received 2019 November 29; revised 2020 April 8; accepted 2020 April 14; published 2020 May 13

Abstract

We monitored the z = 0.158 quasar 3C 273 between 2015 and 2019 in the optical (BVrz) and near-infrared (JHK) with the aim to perform dust reverberation mapping. Accounting for host galaxy and accretion disk contributions, we obtained pure dust light curves in JHK. Cross correlations between the V band and the dust light curves yield an average rest-frame delay for the hot dust of τcent ≈ 410 days. This is a factor of two shorter than that expected from the dust ring radius Rτ ≈ 900 lt-day reported from interferometric studies. The dust covering factor (CF) is about 8%, much smaller than that predicted from the half covering angle of 45° found for active galactic nuclei (AGNs). We analyze the asymmetric shape of the correlation functions and explore whether an inclined biconical bowl-shaped dust torus geometry could bring these findings (τcent, Rτ and CF) into a consistent picture. The hot varying dust emission originates from the edge of the bowl rim with a small covering angle 40° < θ < 45°, and we see only the near side of the biconus. Such a dust gloriole with Rτ = 900 ± 200 lt-day and an inclination 12° matches the data remarkably well. Comparing the results of 3C 273 with literature for less luminous AGN, we find a lag–luminosity relation τ ∝ L0.5 with α = 0.33±0.40, flatter than the widely adopted relation with α ≈ 0.5. We address several explanations for the new lag–luminosity relation.

Unified Astronomy Thesaurus concepts: Reverberation mapping (2019); Active galactic nuclei (16); Photometry (1234); Quasars (1319)

Supporting material: data behind figure

1. Introduction

The quasar paradigm comprises a supermassive black hole, a central X-ray source, an accretion disk (AD), surrounded by a broad line region (BLR), and a molecular dusty torus (TOR) farther out. The three components AD, BLR, and TOR may have smooth transitions between each other rather than being separated entities with sharp boundaries. Of particular interest here is the three-dimensional geometry of the central region and the three components.

As the inner quasar regions cannot be resolved by conventional imaging techniques, reverberation mapping (RM) is the main tool of the trade (Bahcall et al. 1972; Cherepashchuk & Lyutyi 1973; Gaskell & Sparke 1986; Peterson 1993; Horne et al. 2004). RM traces the delayed response of irradiated regions to the light fluctuations of the continuum emission from the inner AD. As a first approximation, the size of the irradiated region can be inferred from the time lag τ. This way, near-infrared (NIR) RM studies of the dusty torus find a radius Rτ = c · τ (Clavel et al. 1989; Suganuma et al. 2006).

1.1. The Size–Luminosity Relation

A remarkable finding is the relation between the reverberation-based size, Rτ, and the active galactic nucleus (AGN) luminosity, L, with Rτ ∝ Lα and α ≈ 0.5 (Suganuma et al. 2006; Gaskell et al. 2007; Koshida et al. 2014; Minezaki et al. 2019). Such a relation with α ≈ 0.5 has been expected, if the hot NIR emitting dust is located in a simple equatorial geometry and Rτ measures the dust sublimation radius, Rsub, inferred from the UV luminosity (Barvainis 1987). This relation may hold the key for cosmological applications to measure quasar distances and to check for dark energy (Kobayashi et al. 1998; Oknianskij 1999; Yoshii 2002; Hönig 2014; Yoshii et al. 2014). However, Rτ is about three times smaller than Rsub (Kishimoto et al. 2007; Koshida et al. 2014). This suggests that internal effects like those from the three-dimensional dust geometry or from a reduced heating of potentially shielded dust clouds (Gaskell et al. 2007) need to be better understood, before cosmological implications from the R–L relation should be drawn.

Before we address such effects, we note that a similar R–L relation had been found between the size of the BLR and the AGN luminosity: in the first observational estimate of the R–L relationship, Koratkar & Gaskell (1991a) found a slope α = 0.33 ± 0.2 for CIV. Subsequently, for Hβ, Kaspi et al. (2000) report α = 0.7 ± 0.03, and then Bentz et al. (2013), after correction of the host galaxy contribution, refined this slope to α = 0.533 ± 0.034. One more piece to the puzzle was added by Du et al. (2016) who reported for AGNs with high accretion rates a shallow slope α ≈ 0.3. Possible explanations for that have been considered, involving the ionization parameter (Czerny et al. 2019). Notably, nearly half a century ago, Dibai (1977) used the Strömgren-type argument and a value of α = 0.33 for calculating the first single-epoch AGN black hole masses, which agree remarkably well with the latest reverberation-based estimates (Bochkarev & Gaskell 2009).
1.2. The Torus Structure

Interferometric K-band measurements with the KECK interferometer (Kishimoto et al. 2009, 2011) and the VLTI/Gravity instrument (GRAVITY Collaboration et al. 2020) resolved the innermost dusty structure of 15 AGN (eight with KECK, eight with VLTI, and 3C 273 in common). The effective ring radii \( R_{\text{ring}} \) derived from the observed visibilities scale roughly with the AGN luminosity \( L^{1/2} \), but the GRAVITY Collaboration et al. (2020) report a relative size decline in the two highest luminosity AGNs. For AGNs with available K-band reverberation measurements, \( R_{\text{ring}} \) is, on average, larger than \( R_{\text{r}} \). Kishimoto et al. (2011) suggested that the interferometric measurements at least partly resolve the dust sublimation zone, and that the ratio \( r = R_{\text{ring}}/R_{\text{r}} \) yields information on the compactness \((r \approx 1)\) or extent \((r > 1)\) of the hot dust distribution. For the entire sample, however, \( R_{\text{ring}} \) is systematically smaller than \( R_{\text{sub}} \). To match \( R_{\text{ring}} \) with \( R_{\text{sub}} \), Kishimoto et al. (2007, 2009) suggested that the dust grain sizes are larger or that the central engine radiation is significantly anisotropic.

Kawaguchi & Mori (2010, 2011) proposed a bowl-shaped dust torus that smoothly continues into the central AD. In their model, the AD emission is anisotropic, as it is the highest toward the polar region and lowest toward the equatorial region. The anisotropy of the AD emission controls the angle-dependent dust sublimation radius and, thus, the concave rim of the bowl, allowing for parts of the dust to lie closer to the AD than \( R_{\text{sub}} \) calculated from the luminosity toward the polar direction. Despite attractive features, however, this model needs to be expanded to account for the influence of the BLR onto the entire system (Goad et al. 2012).

For the well studied Seyfert-1 galaxy NGC 5548, Gaskell et al. (2007) have analyzed the AGN energy budget and derived crucial constraints on the geometry of the BLR and the dust torus: the BLR has a likely covering factor (CF) about 40\%, which translates to a half covering angle \( \theta \approx 25^\circ \), as measured from the equatorial plane. The BLR shields a substantial fraction of the dust torus from direct illumination by the AD, allowing for the observed relatively small \((<20\%)\) NIR contribution to the AGN energy budget.

Goad et al. (2012) combined the findings by Gaskell et al. (2007) and Kawaguchi & Mori (2010, 2011) into a BLR-TOR system confined by a paraboloidal bowl-shaped torus rim where the BLR clouds lie close to and above the rim (their Figure 1). The observer sees only the emission from the near side of the bipolar bowl. The BLR clouds shield part of the dust from the AD radiation at \( \theta < 40^\circ \), so that the hot dust emission arises essentially from the top rim of the bowl at \( 40^\circ < \theta < 45^\circ \). Goad et al. (2012) tested their model with reverberation data of NGC 5548.

Based on high-cadence dust RM observations of the Seyfert-1 WPVS 48, Pozo Nuñez et al. (2014) found an exceptionally sharp NIR echo, which led them to favor that the varying hot dust is essentially located at the edge \((40^\circ < \theta < 45^\circ)\) rather than along the entire bowl rim, which crosses a large range of isodelay surfaces. In a slightly generalized view, Oknyansky et al. (2015) proposed that the hot dust emission comes from the near side of a hollow biconical outflow, which is co-spatial with the isodelay paraboloids, a case requiring that the inclination to the line of sight is small. Based on observations of the Seyfert-1 galaxy 3C 120, with a jet inclination \( i \approx 16^\circ \), Ramolla et al. (2018) found that the hot dust echo is relatively sharp and symmetric in contrast to the more complex broad H\(\alpha\) echo. This is consistent with a paraboloidal bowl model where the BLR is spread over many isodelay surfaces, yielding the smeared and structured H\(\alpha\) echo as observed, while the hot dusty bowl edge matches a relatively narrow range of isodelay contours. The important feature of such a gloriole-like dust emission is the geometric foreshortening effect of the reverberation signal, because the dust lies above the equatorial plane and closer to the observer. While such structure studies have been performed for Seyfert galaxies, i.e., low-luminosity AGNs, they should be extended to higher-luminosity quasars, in order to recognize luminosity-dependent trends.

1.3. 3C 273

3C 273 at \( z = 0.158 \) is the most luminous nearby quasar and may serve as a bench mark for any luminosity-dependent relations. 3C 273 is the brightest quasar, making it an ideal target for observations of any kind.

Based on their 7 yr long RM campaign, Kaspi et al. (2000) determined rest-frame Balmer line lags of \( \tau (\text{H}\alpha) = 443 \) days, \( \tau (\text{H}\beta) = 330 \) days, and \( \tau (\text{H}\gamma) = 265 \) days versus the B-band; here, \( \tau \) is the centroid of the interpolated cross-correlation function. Kishimoto et al. (2011) and GRAVITY Collaboration et al. (2020) reported a dust ring radius of \( R \approx 900 \) lt-day inferred from interferometric K-band measurements.

Yet, to our knowledge, no dedicated dust reverberation mapping campaign of 3C 273 has been performed. Fortunately, Soldi et al. (2008) have collected all published photometry of 3C 273 of the past 50 yr in the ISDC. Geneva, adjusted the photometry from different telescopes, removed flares, and selected the best data. Cross correlating the \( JHK \) with optical and UV light curves, they derived a rest-frame dust lag of \( \tau (K) \sim 1 \pm 0.2 \) yr. An important part of these data are the light curves obtained by Neugebauer & Matthews (1999) at the 5 m Palomar Hale telescope between 1974 and 1998, using a single-element InSb photovoltaic detector and chopping/nodding technique to remove the effects of the sky emission; as described by Soldi et al., these data unfortunately were not available in tabulated form but extracted from the figure.

Remarkably, the dust lag (365 days) is shorter than the H\(\alpha\) lag (443 days), a fact that, at first glance, suggests that the dust torus is smaller than the BLR and, hence, appears to contradict the AGN unified scheme (Antonucci 1993). This led us to embark on a dedicated reverberation campaign of 3C 273, and we here report on the results of the dust reverberation, a re-analysis of Soldi et al.’s data, a comparison with bowl-shaped models and the interferometric measurements, and the impact on the lag–luminosity relation.

Section 2 describes the observations and data. Section 3 shows the light curves, the determination and subtraction of the host galaxy, and the contribution of the AD to the NIR light curves, the properties of the varying dust emission, the dust time lag, and the derivation of the dust CF. Section 4 considers the RM results in the framework of a bowl-shaped TOR geometry using the additional constraints of an interferometric size and a small dust CF. Section 5 discusses the findings and implications. Section 6 provides a summary and conclusions. Throughout this paper, we adopt \( \Omega_m = 0.27, \Omega_{\Lambda} = 0.73, \) and \( H_0 = 73 \) km s\(^{-1}\) Mpc\(^{-1}\) yielding an angular-size distance of 546 Mpc (luminosity distance of 734 Mpc) for 3C 273.

\(^{7}\) http://isdc.unige.ch/3c273/
Table 1

| Filter | $\lambda_{eff}$ (μm) | $f_0$ (Jy) | Avg. Flux (mJy) | Obs. Nights |
|--------|---------------------|-----------|----------------|-------------|
| $B$    | 0.433               | 4266.7    | 23.04 ± 1.39   | 109         |
| $V$    | 0.550               | 3836.3    | 24.34 ± 1.12   | 119         |
| $r$    | 0.623               | 3631.0    | 23.42 ± 1.41   | 128         |
| $z$    | 0.906               | 3631.0    | 24.59 ± 1.57   | 78          |
| $J$    | 1.24                | 1594.0    | 30.09 ± 0.92   | 44          |
| $H$    | 1.65                | 1024.0    | 41.38 ± 1.99   | 24          |
| $K$    | 2.16                | 666.7     | 76.71 ± 3.42   | 77          |

Note. Filters, effective wavelengths $\lambda_{eff}$, zero mag flux $f_0$, average flux, and number of light-curve data points (observed nights).

2. Observations and Data Reduction

3C 273 was observed between 2015 April and 2019 June with semi-robotic optical and NIR telescopes of the Bochum University Observatory near Cerro Armazones (OCA) in Chile\(^8\) (Ramolla et al. 2016). The optical telescopes used are; the 40 cm Bochum Monitoring Telescope (BMT; Ramolla et al. 2013), the 15 cm Robotic Bochum Twin Telescope ROBOTT (formerly named VYSOS 6, for short V6; Haas et al. 2012), the 25 cm BEST-II (Kabath et al. 2009), and the 80 cm infrared telescope IRIS (Hodapp et al. 2010).

Typically, 10–20 dithered images were taken per filter and night and later combined. All images were reduced by the corresponding instrumental data reduction pipelines (dark, bias, and flat correction). Astrometric matching was performed with Scamp (Bertin 2006). Before stacking multiple exposures, they were resampled onto a common coordinate grid with 0″/75 pixel size using Swarp (Bertin et al. 2002); the seeing typically has a point-spread function of $\sim$3″ FWHM. The photometry is performed on combined frames with a fixed 7″/5 aperture found to be the optimum in our previous studies (e.g., Haas et al. 2011; Pozo Nuñez et al. 2014; Ramolla et al. 2018).

The light curves were created using 5–10 nearby (&lt;30′) calibration stars. The optical and NIR absolute flux calibration was performed by comparison with the PANSTARRSS and the 2MASS catalog, respectively; also, airmass-dependent extinction (Patat et al. 2011) and Galactic foreground extinction (Schlafly & Finkbeiner 2011) corrections were applied. A summary on the filters (their effective wavelength and zero flux), the average flux of 3C 273 and total number of observing nights is listed in Table 1.

The time sampling of our light curves is quite coarse, typically with a median of about 4–7 days but only over a few months per year. Since 3C 273 is bright and is nearly daily monitored in the $B$ and $V$ bands by AAVSO\(^9\), we planned to use these light curves if necessary. Fortunately, Zhang et al. (2019) kindly sent us their more comprehensive optical light curves (median $\sim$1 day) between 2008 and 2018, and we used these light curves in addition to ours for the scientific analysis, e.g., cross correlations and modeling.

3. Results

3.1. Optical and Near-infrared Light Curves

Figure 1 shows the optical and NIR light curves of 3C 273. In all optical filters $BVrz$ (open circles), the variations show the same pronounced features: between the years 2015 and 2016, the flux increases by about 20%, then it decreases by 20%–25% during two years until begin of 2018, when it starts to increase again by about 10% through mid-2019. For the NIR light curves of 3C 273 (open triangles), the variations in J resemble those in the optical light curves, but in H and K they differ. The flux in J increases between 2015 and 2016 but not as pronounced as in the optical bands, and then it decreases until 2019. For H and K, the trend is different: instead of a flux increase between 2015 and 2016, a decrease is observed. Then, the K-band shows an increase toward 2017 and a decrease thereafter. Unfortunately, there were no useful J and H data collected in 2017. The difference between JHK suggests that at least in J, the light curve is strongly contaminated by the accretion disk, while in K, the hot dust emission may dominate; H looks like an equal mixture of AD and dust emission. To obtain the pure JHK dust light curves, the contribution of the host galaxy and AD to the NIR bands has to be removed (Section 3.2).

Depending on the telescope availabilities, the light curves of some filters were obtained with different telescopes (BMT, BEST-II, ROBOTT). We checked for telescope-dependent differences between the light curves. We found that any differences are smaller than 1%–2% and that they are due to an additive offset that increases with the native camera pixel size (0″/8 for BMT, 1″/5 for BEST-II, 2″/4 for ROBOTT). This dependence likely comes from a larger host galaxy contribution when the camera has larger native pixels, despite the resampling to a common pixel size of 0″/75 (see Section 2).

We corrected for the flux offsets between BMT, BEST-II, and ROBOTT and scaled the flux to that of the BMT; we note that the inter-telescope corrections were small so that the results, e.g., on the variability features, are essentially unchanged. Figure 2 shows the V-band light curve (after offset correction) plotted with different symbols for the three optical telescopes. In addition, the gray circles show the V-band light curve from the 10 yr monitoring campaign by Zhang et al. (2019). This light curve was essentially obtained with 1.5–2.5 m class telescopes. Both ours and Zhang’s light curves match excellently within the scatter; the scatter at a given short time interval (≈100 days) likely marks the true photometric light-curve uncertainty. It is similar (≈1%) for both light curves.

The full set of our light curves are available in a table that has the following five columns: (1) Filter, (2) Telescope, (3) MJD, (4) Flux (mJy), and (5) Flux error (mJy).

3.2. Construction of the Pure Dust Light Curves

To construct the pure dust light curves, we determined the host galaxy brightness in the optical and extrapolated it to the NIR via model spectral energy distributions (SEDs). Likewise, we determined the AD brightness in the optical and extrapolated it to the NIR via a power law (Kishimoto et al. 2005, 2008). The pure dust light curves are then obtained from the observed NIR light curves after subtraction of the NIR host and AD contributions.

3.2.1. Host Galaxy

Based on HST imaging, Bahcall et al. (1997) found that 3C 273 has an elliptical host galaxy with morphology type E4 and from off-nucleus spectroscopy, Wold et al. (2010) found a

---

\(^8\) https://en.wikipedia.org/wiki/Cerro_Armazones_Observatory

\(^9\) https://www.aavso.org/
2019. For the NIR, note that the decrease between 2015 and 2016 in
derived a rest-frame host galaxy color
of about 14% from a young stellar population and
Figure 2.
features: a 20% flux increase between 2015 and 2016, followed by a softer flux decrease of almost 20% until begin of 2018, and, again, an increase of 10% toward 2019. For the NIR, note that the decrease between 2015 and 2016 in $H$ and $K$ is contrast to the increase in $J$, suggesting that, at least in $J$, the light curve is strongly contaminated by the accretion disk, while in $K$, the hot dust emission dominates; $H$ looks like a mixture of AD and dust emission.

(The data used to create this figure are available.)

Figure 1. 3C 273 normalized light curves: $BVR_z$ are represented as circles and $JHK$ are represented as triangles. All optical filters show the same pronounced variation features: a 20% flux increase between 2015 and 2016, followed by a softer flux decrease of almost 20% until begin of 2018, and, again, an increase of 10% toward 2019. For the NIR, note that the decrease between 2015 and 2016 in $H$ and $K$ is contrast to the increase in $J$, suggesting that, at least in $J$, the light curve is strongly contaminated by the accretion disk, while in $K$, the hot dust emission dominates; $H$ looks like a mixture of AD and dust emission.

The resulting SED template. It is then fit by a spline function (black solid line), and the spline function is shifted to the redshift $z = 0.158$ of 3C 273 (red solid line). Then, we sampled the redshifted spline function at the observed wavelengths of interest (filled black star symbols) and derived the host flux ratios $B/V$ and $r/z$ in the observer’s frame for use in the Flux Variation Gradient (FVG) analysis.

To estimate the host contribution in our data, we applied the FVG method proposed by Choloniewski (1981), further established by Winkler et al. (1992) and Sakata et al. (2010), and successfully applied by, e.g., Haas et al. (2011), Pozo Nuñez et al. (2014), and Ramolla et al. (2018). In this method, for two filters, e.g., $B$ and $V$, the $B$ and $V$ data points obtained in the same night through the same apertures are plotted in a $B$ versus $V$ flux diagram (Figure 4). The important feature is that the flux variations follow a linear relation with a slope $\Gamma$ given by the host-free AGN continuum. In the flux–flux diagram, the host galaxy—including the contribution of line emission from the narrow line region (NLR)—lies on the AGN slope somewhere toward its fainter end. With knowledge of the host colors, i.e., the host flux ratios $B/V$ and $r/z$, the FVG analysis yields the intersection of the AGN slope (blue lines in Figure 4) with the host slope (red dotted lines in Figure 4) and, thus, the host fluxes in the four filters $BVR_z$ marked by green stars in Figure 4 and listed in Table 2. Then, the host SED template in Figure 3 is shifted vertically to fit the $BVR_z$ host fluxes. Finally, this SED allows us to extrapolate the $JHK$ fluxes of the 3C 273 host for our apertures. The values are listed in Table 2. Compared with the total $JHK$ fluxes (Table 1), the host contributes between about 30% in $J$ and 15% in $K$.

Figure 2. $V$-band light curve plotted with different symbols for the three optical telescopes (BMT, BEST-II, and ROBOTT = V6). The data match with each other and with the more comprehensive light curve obtained until 2018 March by Zhang et al. (2019), plotted with gray dots.

contribution of about 14% from a young stellar population and
derived a rest-frame host galaxy color $B - V = 0.77$.

With these constraints at hand, we constructed a rest-frame host SED template for 3C 273 based on the colors of an elliptical host galaxy, as determined for $UBV$ by Fukugita et al. (1995), for Sloan $griz$ filters and $JK$ filters by Chang et al. (2006), and for 2MASS $JHK$, and Spitzer/IRAC filters by Jarrett et al. (2019). Because of the presence of young stars (Wold et al. 2010), we used slightly bluer colors $UBV$, $r - i$, $r - J$, and a slightly shallower 1.6 $\mu$m bump. Figure 3 shows
3.2.2. Accretion Disk

To estimate the spectrum of the AD in $BVrz$, we subtracted the host contribution (Table 2) from the mean total fluxes (Table 1). The result is shown as the blue squares in Figure 5. The power-law fit to the $BVrz$ data points yields $F_\nu \sim \nu^{\alpha}$, with $\alpha = 0.34 \pm 0.06$, in agreement with the spectral index $\alpha = +1/3$ found by Kishimoto et al. (2008) for six quasars. Their study of the NIR component of the AD as seen in polarized light reveals that the AD spectrum continues toward the NIR with the same power-law slope as measured at optical wavelengths. Adopting that this holds also for 3C 273, we take the AD contribution to the NIR bands from the power-law fit with values as labeled at the open squares in Figure 5 and listed in Table 2. The AD contribution to the total NIR fluxes is $J \sim 50\%$, $H \sim 30\%$, and $K \sim 15\%$.

3.2.3. Dust Light Curves

We derived the dust light curves from the observed $JHK$ light curves (Figure 1) by subtraction of both the $JHK$ host galaxy contribution (Table 2) and a suitably scaled light curve of the AD. For this AD light curve, we used the flux-scaled host-subtracted V-band light curve LC($V$). The scaling factor (SF) was determined from the power-law AD extrapolation, e.g., in the $J$ band with values from Table 2: $SF(J) = F_{AD}(J)/F_{AD}(V) = 15.57/21.34$. This yields at the $JHK$ bands, respectively,

$$LC(dust) = LC(total) - F(host) - SF \times LC(V).$$

The resulting dust light curves are shown in Figure 6. Compared to the observed NIR light curves in Figure 1, we find the following changes:

1. In $K$, the shape of the light curve is similar, but the amplitude increases from about 12% to about 20%.

![Figure 5](image_url)

**Figure 5.** $B/V$ and $r/z$ flux–flux diagrams. The black crosses indicate the matched fluxes for every night with their errors, the blue lines represent the AGN slope ± error, and the red dotted lines mark the host flux ratios for an elliptical galaxy derived from the SED in Figure 3. The derived $BVrz$ host fluxes are plotted as a green star.

![Figure 3](image_url)

**Figure 3.** Construction of the 3C 273 host SED, based on colors for an elliptical galaxy with 14% flux contribution from a young stellar population: open diamonds (Fukugita et al. 1995; Wold et al. 2010) and open squares (Chang et al. 2006 and Jarrett et al. 2019). In the rest frame, the black solid line depicts a spline function fitted to the open symbols. The red line shows the spline shifted to the redshift of 3C 273 whereby the red dots correspond to the open symbols in the rest-frame spline. The flux scaling of the template is described in the text (Section 3.2.1). The black filled stars on the red line mark the predicted observed fluxes in the filters of interest with values as labeled.
2. In $H$, the decrease between 2015 and 2016 becomes more pronounced, and the amplitude increases from about 15% to about 30%.

3. In $J$, the shape of the light curve changed; the increase between 2015 and 2016 reverses now to a decrease, similar to what is seen in the $H$ and $K$ bands. The amplitude increases from about 10% to about 40%.

To summarize, compared to the observed NIR light curves, the dust light curves show more coherent variations and stronger amplitudes.

### 3.3. Nature of the Dust Variability

Now, we examine the variability properties of the pure dust emission in the NIR, after subtraction of the host and AD contribution. Figure 7 shows the flux–flux diagrams for the $JHK$ filter pairs. For all pairs ($J/H$, $J/K$, $H/K$), the variations are correlated. This adds confidence that the creation of the dust light curves from the observed NIR light curves by means of subtraction of the host and AD contribution is sound.

The thick red lines in Figure 7 mark the range of color temperatures between the bright and faint states, calculated for Planckian curves in the rest frame of 3C 273. We make the reasonable assumption that the dust grains are at a mix of temperatures. Then, the shorter wavelength filters are more sensitive to the hotter dust grains. This explains the range of measured color temperatures between 1200 and 1800 K. This range is consistent with expected dust temperatures. For comparison, the sublimation temperatures $T_{\text{sub}}$ of graphite dust grains are estimated to be 1500–1900 K (Barvainis 1987; Kishimoto et al. 2007).

For all filter pairs, the color temperatures change by about 5% (i.e., a factor 1.05) between the bright and faint states. For Planckian curves, the luminosity is proportional to the fourth power of the temperature ($L \propto T^4$). With this assumption\textsuperscript{10}, the amplitude of the dust luminosity is then $1.05^{4-1} = 0.2$, i.e., 20%. The amplitude of the $V$-band light curve, i.e., amplitude of the triggering variations from the AD, is about 25% (Figure 11). Thus, the amplitude of the dust luminosity is a bit smaller than that of the triggering variations from the AD. This is consistent with the simple expectation that the echo amplitude does not exceed the amplitude of the driving signal.

The amplitudes are about $(60–50)/55 = 0.18$ in $K$, $(19–14)/16.5 = 0.3$ in $H$, and $(7.75–5.25)/6.5 = 0.39$ in $J$. With decreasing wavelength, the amplitudes of the dust light curves increase and exceed the amplitude of the driving signal. As an explanation for the different $JHK$ amplitudes, we suggest that the filters measure the dust emission on the Wien tail of the Planck function. The sensitivity to temperature changes increases toward shorter wavelengths. This is illustrated in Figure 8. While, a priori, the echo amplitude is not expected to exceed the amplitude of the driving signal, here, we encounter the case of an amplitude amplification, which we call Wien tail amplitude amplification. Because of this amplitude amplification, even in $K$, an amplitude of 0.18 may be an overestimate of the echo amplitude of the luminosity; this may become relevant for the light-curve modeling in Section 4.

In the sections that follow, we will use the dust light curves as derived in $JHK$ from the observed NIR light curves by means of subtraction of the host and AD contribution and adopt the idea that the variations are essentially caused by a change of the mean dust temperatures.

### 3.4. Cross-correlation Analysis

We determined the time lag of the dust variations (echoes) against the AD variations (driving signals) by different\textsuperscript{10}

---

\textsuperscript{10} This assumption holds for dust grains with diameter $a$ larger than the wavelength $\lambda$. For smaller grains, the dust emissivity properties come into play, yielding up to $L \propto \lambda^\beta$ for emissivity exponent $\beta = 2$ (see, e.g., Kruegel 2003).
methods and by direct inspection of the time-shifted light curves. For the AD, we use the combination of the host-subtracted V-band light curves from Xiong et al. (2017), Zhang et al. (2019), and the one in this work.

The cross-correlation functions (CCF) yield the average flux-weighted time lag (Koratkar & Gaskell 1991b; Penston 1991). Our dust light curves are rather sparse. Therefore, we apply the discrete correlation function (DCF) by Edelson & Krolik (1988), which has been designed for sparse and unevenly sampled light curves. We also applied the Z-transformed DCF (ZDCF), which is known to provide more conservative, larger error estimates (Alexander 1997). We also applied the interpolated cross-correlation (ICCF), introduced by Gaskell & Sparke (1986). Its application has proven to work well, if the light curves are well sampled, as is the case at least for the V-band light curve. Additionally, we use the von Neumann mean-square estimator for reverberation mapping data (VNRM) introduced by Chelouche et al. (2017).

The DCF and ICCF centroids are calculated where the correlation value \( r \) is \( r > 0.8 \times I_{\text{max}} \). For the VNRM, the lag corresponds to the minimum of the VNRM estimator and for the ZDCF to the maximal likelihood. The estimation of the lag uncertainty in the DCF, ICCF, and VNRM is calculated via the flux randomization/random subset selection method (FR/RSS) by Peterson et al. (1998), here applied to 2000 modified light curves. In the case of the ZDCF error estimation, the default parameters were used.

### 3.4.1. Time Lag of the Dust Emission

Figure 9 shows the DCF together with the ICCF for the three filter combinations V/J (top panel), V/H (middle panel), and V/K (bottom panel), and the ICCF is shifted up by 0.5. The DCFs in Figure 9 show two prominent peaks at \( \sim 500 \) and \( \sim 850 \) days for the three filters. Also, the lag range between 1300 and 1500 days shows a correlation value larger than 0.5 (noisy for H-band), and the long lag peak at \( \sim 1400 \) days is also present in the ICCF for the three filters. For J and H, the ICCF does not show the two main peaks (at \( \sim 500 \) and \( \sim 850 \) days); rather, they are smooth together, which points out the problem of the interpolation when one of the light curves (trigger or echo) has long gaps. Our J and H light curves are poorly sampled, and one observation season (2017, see Figure 6) with a pronounced turn-up of the K-band light curve is missing in J and H. For the K band, the peak at \( \sim 850 \) days essentially disappears (in the ICCF). Figure A1 in the Appendix presents all of the CCFs obtained with the different methods for the three filters, showing that all methods are consistent with each other.

Since our NIR campaign is only 1500 days long, we are not able to confirm/reject lags on this long timescale. In order to check whether the long time lags are real (\( \sim 800 \) and \( \sim 1500 \) days present in the CCF in Figure 9), we make use of the 30 yr long light curves collected by Soldi et al. (2008). We subtract the AD contribution in JHK, using the V-band light curve minus host (6% of the average V-band flux; Bentz et al. 2013, Table 12) and \( F_\nu \propto \nu^{0.34} \) (as for the OCA data, see Figure 5), and compute the DCF, ICCF, ZDCF, and VNRM between the dust light curves and the V-band light curve. The results for the DCF and ICCF are shown in Figure 10, where the ICCF is shifted up by 0.5. All filters show a maximal correlation value of \( \sim 0.5 \) located between 300 and 700 days. None of these correlations shows any evidence favoring the long delays at about 800 and 1400 days (see also Figure A1 in the Appendix for all of the CCF in the three filters). We found an average time delay for JHK in the observer frame using the DCF \( \tau = 600 \pm 60 \) days, ICCF \( \tau = 550 \pm 50 \) days, ZDCF \( \tau = 510 \pm 120 \) days, and VNRM \( \tau = 520 \pm 30 \) days. The lag values are slightly larger than the one reported in their study (\( \tau_{\text{obs}} \sim 420 \pm 84 \) days; \( \tau_{\text{rest}} \sim 365 \pm 73 \) days). However, their
shorter lags can be explained by the contribution of the AD autocorrelation. This contribution is wavelength dependent and shifts the cross-correlation values to smaller lags. The CCF shapes and the time delays found for the Soldi et al. (2008) data lead us to conclude that, for our OCA campaign, the lag has to be searched between 200 and 800 days.

The time lags found for our NIR observing campaign are listed in Table 3. For all three filters, $JHK$, the time lags obtained via the DCF are consistent with each other within the errors. For the ICCF, the $J$ and $H$ lag values show very large errors and, hence, are less trustable. Even worse, the two main correlation peaks (at 500 and 850 days) are merged together (see Figure 9), a fact that could be explained by the interpolation of the $J$ and $H$ light curves across the gap between 2016 and 2018. For the $K$-band correlation, the ICCF lag (420 days) is smaller compared to the DCF (~510 days) and ZDCF (~550 days) but agrees with the VNRM (~410 days). For the best sampled dust light curve, $K$ band, the $V/K$ correlation lies between 400 and 550 days taking all of the CCF methods, with an average delay of ~475 days.

The light curves show clear variation patterns, allowing us to check visually via back-shifting whether the different lag estimates appear consistent with the data. Figure 11 shows the overlay of the AD and the back-shifted dust light curves, with a back-shift of 400 days. In fact, the variation patterns match well, but a spread or tolerance of ~100 days for the back-shift should be adopted. A visually determined lag of 400 ± 100 days is consistent with the broad cross-correlation function and the time lag calculations from Table 3.

The rest wavelengths of $JHK$ are 1.08, 1.42, and 1.86 $\mu$m. The data do not indicate a significant trend of a lag shortening with decreasing wavelength (only in the case of the ZDCF, but with large errors specially in $J$, as has sometimes been reported, e.g., Tomita et al. (2006). Thus, our data of 3C 273 are in line with the relative wavelength independence of NIR lags reported by Oknyansky et al. (2015), which they attribute to a specific geometry for the dust.

In our data, the $K$-band lag is more reliable than the $J$- and $H$-band lags due to a better time sampling, and likewise in Soldi et al. (2008), the uncertainty of the AD subtraction is larger in $J$ and $H$ than in $K$. Therefore, for both data sets, we adopt the $K$-band lag as the optimal time lag for the hot dust.
Table 3 lists the K-band lag in days obtained with the different methods for the Soldi et al. light curves (fourth column). The lags for this work are, in general, shorter; only the ZDCF shows a slightly longer lag in the OCA campaign, but its error is high. We take as the final delay for the hot dust the average time lag in K from the four CCF methods, because the results are consistent with each other within the errors. Table 3 shows that for this work, we obtain a K-delay of $\tau_{K,\text{obs}} = 474^{+24}_{-22}$ days, which, in the rest frame, corresponds to $\tau_{K,\text{rest}} = 409^{+21}_{-61}$ days. The average lag of the OCA observation is about 10% shorter than that found for the Soldi et al. (2008) data. Our shorter delays may be explained by the fact that the 3C 273 luminosity during the OCA campaign is about 28% lower than during the prior 30 yr.\(^{11}\)

3.4.2. Possible Asymmetry of the Cross Correlation

In the limit of infinite sampling, the CCF between the driving signal and its echo is equivalent to the convolution of the transfer function (TF) with the autocorrelation function (ACF) of the driving signal. Thus, the CCF may reveal higher-order moments, e.g., asymmetries, of the TF.

Figure 12 shows the DCF, ICFF, ZDCF, and VNRM estimator between the V and K light curves within the time range of interest, until 800 days. All CCFs show a broad correlation between 200 and 600 days. The DCFs exhibit an interesting asymmetry: a peak at around 500–550 days with a steep decline toward longer delays and a broad shoulder to shorter delays down to about 250 days. On the other hand, the ICCF does not show a peak at 500–550 days but instead at ~400 days, and the correlation is more symmetric. The ZDCF and VNRM estimators show broader correlations but also a steep decline between ~550 and ~600 days.

We also inspected the CCF shape using the best sampled part of the Soldi et al. (2008) light curves between 1984 January and 1994 December with a median V and NIR sampling of around 7 and 22 days, respectively. The computed CCFs are shown in Figure 13. For all of the CCF methods, the cross correlations show a similar asymmetric shape. The DCF and ICCF show a peak at about 700 days, a steep decline to longer lags reaching the zero level at about 900 days, and a shallow tail reaching the zero level at about 200 days; this shallow tail even reveals mildly a secondary peak at about 350 days. In the case of the VNRM estimator, the asymmetry and the secondary peak are also present, but they are located at shorter lags, at around 200 days and 500 days, respectively. We come back to this asymmetric CCF shape in Section 4.

Finally, we mention that there exist some differences in the CCF shapes when using all of the observation data of Soldi et al. (2008), 30 yr, and when using only a part of these observations, 11 yr. These CCF differences may point to the presence of anomalous responses of the echo to the continuum variations as reported by Gaskell et al. (2019) for the H$\beta$ BLR of the Seyfert-1 NGC 5548 and a sample of other AGNs including the PG quasars. As discussed by Gaskell et al. (2019), such anomalies best show up when inspecting the light curves, and they could be caused by, e.g., anisotropic continuum emission or absorbing clouds. Nevertheless, here, for the dust reverberation of 3C 273, we do not delve further into these details.

3.5. Dust Covering Factor

The UV to NIR SED allows us to estimate the CF of the hot dust. If the dust grains completely re-emit the absorbed UV radiation in the infrared, then the CF is defined as $\text{CF} = \Omega/4\pi = L_{\text{IR}}/L_{\text{UV}}$, where $L_{\text{IR}}$ is the total IR luminosity of the dust, and $L_{\text{UV}}$ is the total UV luminosity from the AD. The CF can be approximated by the peak luminosities (Landt et al. 2011) such that

$$\text{CF} = 0.4 \times \frac{\nu_{K}L_{K}}{\nu_{\text{UV}}L_{\text{UV}}}.$$

For 3C 273, we obtain $\text{CF} \sim 0.08$. This agrees with the findings of Landt et al. (2011) for a sample of 23 type-1 AGNs, where $\text{CF} \sim 0.01–0.6$ with an average of $\langle\text{CF}\rangle = 0.07 \pm 0.02$.

A small CF suggests that the NIR dust emission originates in a small angular range seen by the AD. For a thin ring at $40^\circ < \theta < 45^\circ$ with $\theta$ measured against the equatorial plane, the dust covering fraction is about $\text{CF} = 0.06$. We elaborate on this issue in Section 4.

4. Bowl-shaped Geometry

Kishimoto et al. (2011) performed K-band interferometric measurements of 3C 273. Modeling the visibility with a thin dust ring, they found an angular size of $0.81 \pm 0.34$ pc ($933 \pm 392$ lt-day for the cosmology adopted here). Recently, the GRAVITY Collaboration et al. (2020) found a similar angular size of $0.28 \pm 0.03$ mas, which—adopting a Gaussian FHWM—corresponds to a dust radius size of $0.567 \pm 0.106$ pc $= 675 \pm 126$ lt-day and translates to a ring radius of about 900 lt-day. On the other hand, with the RM technique, we obtain an average rest-frame time lag of $\sim 410$ days. This is a factor of two lower than expected, if both methods see the same dust emission and if the dust were located in the equatorial plane of the AGN.

Interferometry measures the projected size of the NIR emitting dust as seen from the observer and does not take into account the vertical structure of the dust. If the NIR emitting dust is not located in the equatorial plane but closer to the

---

\(^{11}\) The host-subtracted V-band flux for this work is $\text{AD}_{\text{OCA}} = F_{\text{total}} - F_{\text{host}} \sim 21.3$ mJy (Table 2). For Soldi et al., it is about 27.5 mJy, obtained from $F_{\text{total}} = 29–30$ mJy (their Table 1) and subtracting 6% host contribution (Bentz et al. 2013, Table 12). Then, the flux ratio is $\text{AD}_{\text{Soldi}}/2008/\text{AD}_{\text{OCA}} \sim 1.28.$
observer than the AD, then reverberation mapping will produce a foreshortening effect, i.e., yield about 2–3 times shorter time lags, as has been discussed in Pozo Nuñez et al. (2014, see their Figure 6) and in Oknyansky et al. (2013, see their Figures 2 and 3). In this section, we explore how far the difference between the interferometric values and our RM value can be explained by a special geometry of the dust emitting zone.

Here, we consider a paraboloidal bowl geometry, following Goad et al. (2012). The height $H$ of the bowl rim is $H \propto R_*^2$, with $R_*$ being the radius in the equatorial plane. First, we adopt a half-opening angle $\theta = 45^\circ$ statistically justified by the fraction of type-1 to type-2 AGNs (Barthel 1989; Huchra & Burg 1992), and an inclination $i = 12^\circ$ based on the orientation of the radio jet axis against the line of sight to the observer (Lobanov & Zensus 2001; Savolainen et al. 2006; Jorstad et al. 2017).

Figure 14 (left panel) shows such a bowl geometry with an equatorial radius of $R_* = 900$ lt-day, as the reported interferometric dust ring radius. A face-on bowl is plotted as a thick black line, and a bowl with $i = 12^\circ$ is plotted as thick blue lines. Since the dust CF found in Section 3.5 is very low, we assume a small area where the dust emission occurs. As proposed by Goad et al. (2012), it is located on the edge of the bowl-shaped dust torus, between $40^\circ < \theta < 45^\circ$ and marked with thick red lines (where $\theta$ is measured against the equatorial plane). The isodelay contours are marked with thin black lines and labeled with the corresponding time lags.

Note that the complete model is actually a biconical bowl model, but that in this model, the observer only sees the front side of the bowl; the back side below the equatorial plane is hidden (i.e., highly absorbed).

4.1. Transfer Function for the Bowl-shaped Geometry

We calculated the TF for different bowl sizes with an inclination angle of $12^\circ$ and an emission range of the dust rim of $40^\circ < \theta < 45^\circ$.

The TF was calculated as follows: we sampled the dust rim in 3D space as seen from the observer to a grid of 1 lt-day cell size, computed the lag for each cell, and calculated the TF as histogram over the cells. While this TF is just a geometric approximation and does not account for clumpy dust structures and the possible shadowing of dust clouds, it allows us to draw basic conclusions.

Figure 14 (right panel) shows an example of the TF for a fixed bowl size of 900 lt-day and a dust emitting region $40^\circ < \theta < 45^\circ$. It shows the TF in the rest frame (black) and redshifted ($z = 0.158$) to the observer’s frame (green).

The TF shows a pronounced double-horned profile. For comparison of our TF at inclination $12^\circ$ with the more sophisticated TFs calculated by Kawaguchi & Mori (2011), we refer to their Figure 4, which shows the similarly double-horned TF of an optically thin torus at inclination $25^\circ$. Kawaguchi & Mori (2011) performed a clumpy torus calculation and presented plenty of TF details for different torus sections, e.g., waning effect, shielding of clumps (optically thickness), and even how much the observer may see from the torus back side, i.e., from below the equatorial plane. Here, in our observational paper, we skip these details and continue the analysis with the geometric TF shown in Figure 14.

As mentioned above (Section 3.4), the cross correlation between the driving signal and its echo is equivalent to the convolution of the TF with the ACF of the driving signal. In Figure 14, the convolution of the TF (rest) with a kernel is also shown. The results are similar for different kernel shapes and widths and, hence, quite stable against the details of the kernel. Here, we used a triangular kernel of a 300 days baseline (in the rest frame) as an approximation, which was derived from the autocorrelation of the V-band light curve shown in Zhang et al. (2019), their Figure 4. The resulting convolved TF in the rest frame is plotted in blue, and the observers frame is plotted in red. The convolved TF (obs) has a broad peak at about 550 days and a short-$\tau$ tail reaching about 200 days (Figure 14,
In Section 4.1, we compare this TF with those shown in Figure 4 of Kawaguchi & Mori. The lines represent the signal light curve convolved with different TF_{obs}. Red points show the dust light curve in the K band. The parameters of the bowl models are labeled.

Figure 15 shows modeled echo light curves for some bowl sizes R_{x}, i = 12° and 40° < θ < 45°. The lines represent the signal light curve convolved with different TF_{obs}. Red points show the dust light curve in the K band. The parameters of the bowl models are labeled.

4.2. Modeling the Dust Echo Light Curves

We checked the bowl model further using the light curves directly. For the driving signal, we used the host-subtracted V-band light curve, and to reduce high-frequency noise, we smoothed the signal light curve with a box car function (box size 100 days). We convolved the signal light curve with TF_{obs}, the transfer function in the observers frame, yielding the modeled echo light curve. Note that all calculations are made in the observers frame.

Figure 15 shows modeled echo light curves for some bowl sizes R_{x} around the dust interferometric radius, between 700 and 1100 lt-day. Each model is plotted as a colored solid line and labeled in the inset table with the bowl size R_{x}, χ^2, and the time lag (found via VNRM and DCF centroid) between the AD signal and the modeled echo light curves. The echo models yield a large amplitude comparable to that of the signal light curve.

The best (i.e., smallest) χ^2 is reached for R_{x} = 700 days (Table 4). However, for this bowl size, the average time lag, τ_{AD}=700 ± 400 days, is shorter than the average observed τ_{K obs} = 475 days (Table 3). On the other hand, a bowl size of R_{x} = 900 lt-day yields the best lag agreement between the model and data, while the χ^2 values are not optimal. The χ^2 values depend not only on the match of the lags but also on the match of the amplitudes. Because of the Wien tail amplification of the NIR dust light curves (Figure 8), we suggest that the K-band amplitude is too large to properly match even the best model.

Even with a relatively poor χ^2, the average delays found for the echo light curves for bowl-sizes R_{x} = 900 ± 200 lt-day agree with the observed delay range found via CCF techniques (Table 3). The exact determination of the bowl-model parameters requires more data. Nevertheless, the modeling leads us to conclude the following: if the dust emission comes from an inclined ring above the equatorial plane of the AGN, it produces both a foreshortening effect and a large amplitude variation of the dust echo consistent with the observations.

Table 4

| R_{x} (lt-day) | θ (°) | τ_{avg} (days) | χ^2 |
|----------------|-------|----------------|-----|
| 700            | 40-45 | 390 ± 10       | 2.26|
| 800            | 40-45 | 430 ± 15       | 3.51|
| 900            | 40-45 | 470 ± 40       | 4.45|
| 1000           | 40-45 | 510 ± 60       | 5.78|
| 1100           | 40-45 | 540 ± 100      | 7.26|

5. Discussion

We found a hot dust lag in the K band of τ_{rest} ~ 410 days for the luminous quasar 3C 273, consistent with the lag τ_{rest} ~ 460 days obtained using Soldi et al.’s 30 yr light curves (after AD
5.1. On the Dust Geometry

In order to bring the observational constraints into a consistent picture, we considered a bowl-shaped torus geometry as proposed by Goad et al. (2012), where the dust emission originates from the edge of the bowl rim with a small covering angle $40^\circ < \theta < 45^\circ$, as justified by the small CF ($\theta$ is measured against the equatorial plane). We used an inclination angle of $12^\circ$ indicated from radio jet studies (Lobanov & Zensus 2001; Savolainen et al. 2006; Jorstad et al. 2017). It is clear that the exact parameters of the bowl are not uniquely determined and—in the frame of this observational paper—we have to be restricted to some reasonable cases. We also did not consider clumpy dust distributions; this should not affect our results as long as the BLR shields the bulk of the dust (at $0^\circ < \theta < 40^\circ$) from heating by the AD.

For an inclined bowl model, the (simple geometric) TF is double-horned and yields an asymmetric cross correlation similar to that found in the data. The convolution of the TF with the host-subtracted $V$-band light curve (as proxy for triggering signal light curve) yields the echo light curve. The modeled echo light curves for different equatorial sizes $R_\theta$ around the interferometry radius ($R_\gamma = 900 \pm 200$ lt-day) are in agreement with the observed $K$-band dust light curve, with the average time delay, and with the CCF shape.

Oknyansky et al. (2015) presented in their Figures 2 and 3 a dust-cone geometry, where the walls of the cone coincide essentially with an isodelay surface. This “OGS-model” looks quite similar to that in Figure 14, which is based on the model of Goad et al. (2012). The difference between the two models is that OGS’s dust cone reaches from the equatorial plane up to about $\theta = 45^\circ$, and thus, it has a much larger covering angle ($>30^\circ$) seen from the AD than the dust gloriole in the “GKR-model” of Goad et al. (2012). To bring the covering angle of the dust cone into agreement with the small ($8\%$) dust covering fraction (Section 3.5), Gaskell et al. (2007) had already proposed a shielding of the dust wall by, for instance, randomly distributed BLR clouds located between the AD and dust wall (their Figure 10). Then, despite a large covering angle, the intensity of the AD’s radiation field reaching the dust wall was reduced by the absorption in the BLR, and this may lead to the net effect of the calculation of a small CF. We have checked whether the available data are able to distinguish between the two models. We calculated the geometric TF for the OGS-model in the same manner as for the GKR-model. For $i = 12^\circ$ and $R_\gamma = 900$ lt-day, the TF is also double-horned and shows—after convolution with a triangle kernel with a 300 days baseline—an asymmetric profile, similar to that of the GKR-model depicted in Figure 14 (right panel). Because the two TFs are so similar, the current data will not allow us to distinguish between the two models. Likewise, the current interferometry data are too sparse and uncertain to allow for discriminating between the dust gloriole (sharp ring) and the dust cone (smeared ring seen in projection). Note that both models yield the foreshortened lags.

As is sometimes the case, the reality may lie in a synthesis or mixture of the two models. Such a refined model could be a dust cone whereby the density of the BLR clouds located between the AD and dust wall decreases with increasing $\theta$. This results in a shielding of the wall that is large close to the equatorial plane and decreases toward the cone edge at $\theta = 45^\circ$. This refined model can also be described as a gloriole-like cone with a short wall extension toward the equatorial plane (so that the covering angle becomes larger than the $\sim 5^\circ$ wide ring) and some BLR clouds located between the AD and dust wall producing sufficient extinction (so that the net resulting dust CF remains small). In the net effect, both model descriptions are equivalent. While the final answer must be left for future study, for simplicity, here, we will continue with the “dust-gloriole” model.

It follows that the important conclusion is that the hot dust emission of 3C 273 comes essentially from a gloriole-like inclined ring (or the upper part of a cone) located above the equatorial plane of the AGN. Commonly, the sublimation radius $R_{\text{sub}}$ is estimated following Barvainis (1987) and Koshida et al. (2014), which is based on the assumption that all UV photons from the AD reach the dust zone without absorption by BLR gas, as Gaskell et al. (2007) point out. If the hot dust is essentially located at the bowl edge ($\theta \approx 45^\circ$), then $R_{\text{sub}}$, i.e., the three-dimensional distance of the dust from the AD, becomes larger than $R_\gamma$, namely: $R_{\text{sub}} = R_\gamma / \cos \theta \approx 1.4 \cdot R_\gamma$ for $\theta \sim 45^\circ$. This may explain—at least partly—why $R_{\text{sub}}$ is larger than the interferometric ring size $R_{\text{ang}}$ measured for some sources by Kishimoto et al. (2007, 2011). Likewise, with $R_\gamma = c \cdot \tau$, one obtains $R_{\text{sub}}/R_\gamma = 1/\cos \theta \sim 1 \approx 0.4$ because of the geometric foreshortening effect of the reverberation signal. Then, $R_{\text{sub}}$ is expected to be about a factor $1.4/0.4 = 3.5$ larger than $R_\gamma$.

Next, we briefly address some alternative models. Czerny & Hryniewicz (2011) and Czerny et al. (2017) considered the origin of the BLR and proposed the dusty outflow model where the dust clouds are radiatively accelerated. Likewise, Oknyansky et al. (2015) proposed that the hot dust emission comes from the near side of a hollow biconical outflow. Moreover, to explain the changing-look AGN NGC2617 Oknyansky et al. (2018) proposed that occasionally swirling hot dust clouds populate even the AGN polar region. For the Seyfert 2 NGC 1068, Braatz et al. (1993) and Cameron et al. (1993) resolved the mid-IR emission to be aligned with the [O III] ionization cone, i.e., perpendicular to the dust torus plane. This is unexpected within the AGN unified model (Antonucci 1993). Bock et al. (2000) explains this polar dust emission as a strongly beamed re-emission from the nuclear radiation. Based on interferometry, Höing et al. (2013) also observed a polar mid-IR emission for the Seyfert 1 NGC 3788, and they proposed that the polar dust may originate from a dusty wind that is driven by radiation within the hot region of the dust torus.

According to the AGN unified scheme, the BLR should lie inside the dust torus. We checked whether the published BLR lag measurements of 3C 273 are consistent with the rest-frame dust lag of $\tau_{\text{rest}} \sim 410$ days and a torus radius $R_\gamma \approx 900$ lt-day. From their 7 yr long reverberation campaign, Kaspi et al. (2000) reported Balmer line lags $\tau_{\gamma}$ against the $5100 \, \text{Å}$ continuum of $H_{\alpha} \sim 440$ days, $H_\beta \sim 330$ days, and $H_\gamma \sim 265$ days (their Table 6, here converted to rest-frame lags).

These lags are consistent with the lags for $H_\beta$, $H_\gamma \sim 260$ days (rest frame) reported by Zhang et al. (2019); for compatibility, we consider the lag values without detrending (listed in their Table 7).

Figure 16 presents the rest-frame lags in days for $H_\beta$, $H_\gamma$, $H_\alpha$, and NIR $K$ band for the monitor campaigns in the 1990s (Kaspi et al. 2000; Soldi et al. 2008) and in the 2010s.
(Zhang et al. 2019 and this work). In the 1990s, the dust lag is longer than the BLR lags, consistent with the unified scheme.

However, the difference between dust lag and BLR lags is small, in particular for Hα. This may be explained—at least partly—in the bowl model by the foreshortening effect. While the dust lag suffers from a strong foreshortening effect, the foreshortening in the bowl model by the foreshortening effect. While the dust—

Finally, we note a direct consequence of the dust torus geometry for cosmological applications. For the nearby Seyfert-1 NGC 4151, Höning et al. (2014) calculated a dust-parallax distance, based on dust RM data and interferometric size measurements. Likewise, the GRAVITY Collaboration et al. (2020) tried to do so for three AGNs (Mrk 335, Mrk 509, and NGC 3783), however, with an extreme scatter. If the bowl model is true, then the lags should be converted to real $R_e$, also taking into account the inclination of the bowl.12 In principle, parallax distances could be derived for 3C 273 as well, but we think that the uncertainty of the current data is by far too large to allow for a reliable angular distance calculation.

5.2. On the Lag–Luminosity Relation

Figure 17 (top panel) shows the lag–luminosity diagram for two different NIR dust RM data sets, one from our OCA campaigns and one from the MAGNUM observations (Koshida et al. 2014; Minezaki et al. 2019, hereafter K14 and M19).

The analyzed and published dust RM observations from OCA are on four sources (PGC 50427, WPVS 48, 3C 120, and 3C 273). All lags refer to $\tau_{\text{cent}}$. WPVS 48 was observed during two independent campaigns in 2013 and 2014 yielding—within the errors—the same lags (Pozo Nuñez et al. 2014; Figaredo 2018); here, we take the average lag. Our dust reverberation campaign of 3C 120 took place in 2014–2015, one year after the factor-of-three brightness outburst in 2013, which lasted until 2016 (Ramolla et al. 2015, 2018). Within the short time span between the beginning of the outburst and our reverberation campaign, the dust geometry might not have changed significantly, and any large size changes are unlikely. Therefore, we corrected the luminosity measured in 2014–2015 down by a factor of three to match the luminosity before the outburst. Table 5 lists the rest-frame lags and luminosities used. A linear fit to the four sources (blue data points in Figure 17, top panel) yields a slope $\alpha = 0.33 \pm 0.01$ for the lag–luminosity relation. For comparison, the black dashed line marks a slope with $\alpha = 0.5$, which is widely adopted (Barvainis 1987; Koshida et al. 2014; Yoshii et al. 2014; Minezaki et al. 2019).

---

12 For a bowl model at fixed $R_e$ and $\theta$ ranges, the dust lag strongly increases with inclination, e.g., for $i = 0^\circ$ and $i = 45^\circ$, the (simple geometric) TFs yield $\tau_{50} \sim 2 \times \tau_{45}$, because the TF is dominated by that side of the bowl, which is tilted away from the observer. This questions a widely made assumption (Hönig et al. 2014): “For reverberation mapping, however, inclination only broadens or smooths the time lag signal symmetrically around the mean without a significant shift in $\tau$.” Nevertheless, NGC 4151 lies at $i \sim 45^\circ$, so that in the bowl model $R_e \sim \tau_{45}$ and the derived parallax distance should be correct.
Table 5
OCA Dust RM Sample

| Object   | z    | τ_{K,rest} (days) | log(L'_K) (erg s^{-1}) |
|----------|------|-------------------|------------------------|
| PGC 50427 | 0.024 | 46.2 ± 2.6       | 43.0 ± 0.12            |
| WPVS 48  | 0.037 | 68 ± 5            | 43.40 ± 0.10           |
| 3C 120   | 0.033 | 95 ± 6            | 43.84 ± 0.19           |
| 3C 273   | 0.158 | 410 ± 40          | 45.82 ± 0.15           |

Note.

* Brightness reduced by a factor of three to get the pre-outburst luminosity.

Figure 17 shows also the MAGNUM dust reverberation data from K14 and M19 as red squares and stars, respectively. These lags were derived using the JAVELIN software (Zu et al. 2011); while JAVELIN lags are basically similar to other CCF lags, we do not know whether a bias could be present, and therefore, we here consider the MAGNUM lags separately from the OCA lags. The MAGNUM sample comprises 41 sources (17 sources from K14 and 24 sources from M19), making it the largest homogeneously obtained dust RM set. All data are re-analyzed by M19; we used the observed lags from their Table 3 column 3 (labeled α_{GR} = 1/3, the optical-NIR power-law index of the AD) and their Table 6, and we corrected the observed lags for time dilation 1/(1 + z). Strikingly, a linear fit to these MAGNUM data (all red points) yields a slope α = 0.34 ± 0.03. Figure 17 also shows the residuals (data/fit); the left bottom panel shows slope 0.5, and the right bottom panel shows slope 0.34. Fitting all MAGNUM and OCA lags together yields a slope α = 0.339 ± 0.024. A fit excluding the three sources with log(L) > 45 erg s^{-1} yields α = 0.338 ± 0.030. Thus, the slope is not biased by a few luminous sources.13

When observing in a fixed NIR band, the rest-frame wavelength of the observed dust emission becomes shorter at larger redshifts. In an attempt to account for this, Minezaki et al. (2019) derived a sophisticated wavelength-dependent correction for the lags by multiplying by a redshift term τ_{corr} = (1 + z)^{1.18}. These wavelength-dependent corrected rest-frame lags are listed in their Table 3 column 6. In the lag–luminosity diagram (Figure 18), the lags become larger than without that correction (Figure 17). The correction shifts the luminous sources more upwards, because they are typically at higher redshifts (up to z = 0.6) than the low-luminosity sources. We also applied the correction to our OCA data, shown with blue colors in Figure 18. The fitted slope of 0.33 ± 0.01 remains about the same as that without correction, because all OCA sources are at small redshifts (z < 0.158). We fitted the corresponding lag–luminosity relation for the different data sets, yielding slopes of 0.39 ± 0.045 (for K14 only), 0.37 ± 0.050 (for M19 only), 0.40 ± 0.027 (for the combined K14 and M19 data), and 0.38 ± 0.028 (for the combined OCA and MAGNUM data). These slopes are steeper than those without the wavelength-dependent correction but significantly (at the 3σ level) shallower than the slope 0.5. At the high-luminosity range (log L > 45 erg s^{-1}), 3C 273 shows a relatively small lag compared to the two other quasars (PG 0953 + 414, SDSS J0957−0023) but within the scatter (see residual plot in the bottom right panel of Figure 18). Minezaki et al. (2019) already noticed the exceptional position of 3C 273 based on the lags by Soldi et al. (2008) and tentatively attributed it to the radio-loudness of 3C 273. However, the two other quasars are radio-quiet, and a luminosity enhancement by the optical emission of a radio component does not explain the shallow slopes.

A matter of a debate is the wavelength dependence of the dust reverberation lag, considered here versus the optical UBVR bands, most commonly the B or V band. While the J band is more sensitive to hotter dust than the H and K bands, it appears reasonable to expect a mix of hot dust temperatures for each spatial location (Oknyansky et al. 2015). There is no doubt that mid-infrared lags are longer than NIR lags, which led to the common interpretation that the cooler dust emission arises from a larger distance to the central heating source. Several groups found a longer lag at L (∼ 3.6 μm) or M (∼ 4.8 μm) compared to the J or K bands, e.g., Glass (2004), Figaredo et al. (2018), and Lyu et al. (2019). Based on sophisticated modeling of very sparse WISE observations, Lyu et al. (2019) report a lag ratio K: L: M = 0.6 : 1 : 1.2, while Figaredo et al. (2018) find J: K: L: M = 0.7 : 0.7 : 1.1 : 1.2 for the Seyfert WPVS48, employing the combination of ground-based J, K, and Spitzer – IRAC1/2 monitoring. Notably, neither Glass (2004) nor Figaredo et al. (2018) found significant differences in the lags between rest frame 1 and 2 μm; typically, any NIR lag differences are less than 5% of the optical-NIR lag and not significant at the 3σ level. The same holds true for several other AGNs with dust lags jointly determined in JK. Therefore, we believe that the wavelength-dependent lag correction applied in their paper on the C IV 1549 lag–luminosity relation, Koratkar & Gaskell (1991a) noticed the exceptional position of 3C 273 with respect to a slope α = 0.5 (see their Figure 1). In that paper, 3C 273 was the only source at the luminous end of the relation. A simple check on the reliability of a relation is to remove the four extremes, each one at the top, bottom, left, and right of the diagram. Consequently, to bring the position of this single source into agreement with α = 0.5, they suggested that the luminosity of 3C 273 is an outlier and could be enhanced by the beaming of the continuum associated with the radio source. This possibility can largely be ruled out here, with the help of the two additional luminous radio-quiet sources in the sample of M19 (Figure 17).
Finally, we address two more possible lines for explaining the shallow lag–luminosity slope between 0.33 and 0.4.

(1) Strömgren behavior: We consider the case that the lag–luminosity relation implies a relation between luminosity and the sublimation radius \( R_{\text{sub}} = f \cdot c \cdot \tau \sim L^\alpha \) where slope \( \alpha = 1/3 \), \( c \) is the speed of light, and \( f \) is a scaling factor. The relation with slope \( \alpha = 1/3 \) is strikingly reminiscent of the well-known size–luminosity relation for HII regions, where \( R_{\text{HI}} \sim L^{1/3} \) (Strömgren 1939; McCullough 2000). An explanation of the analogy between \( R_{\text{sub}} \) and \( R_{\text{HI}} \) follows.

For HII regions, the Strömgren radius \( R_{\text{HI}} \) describes up to which distance from the ionizing star the radiation field is strong enough to ionize, e.g., the hydrogen atoms. Beyond \( R_{\text{HI}} \), the radiation field is too weak so that the atoms “survive” unaffected. The reason for the slope \( \alpha = 1/3 \) for the Strömgren relation is that interjacent material inside \( R_{\text{HI}} \) absorbs the radiation from the ionizing star.

For the dust in AGNs, we deal with the sublimation radius \( R_{\text{sub}} \). Inside of \( R_{\text{sub}} \) the AGN radiation field is sufficiently strong so that the dust grains evaporate (analogous to becoming ionized). Outside of \( R_{\text{sub}} \), the radiation field is too weak, so the dust grains are able to survive. So far, the assumption was made that the (dust heating UV) photons of the AD travel all the way until \( R_{\text{sub}} \) without being absorbed by interjacent material. This led to the widely accepted relation \( R_{\text{sub}} \propto L^{1/2} \). However, if sufficient absorbing material lies between the AD and the dust grains, then \( R_{\text{sub}} \) becomes smaller, and this will lead to a shallower slope \( \alpha < 1/2 \). Then, the slope 0.34 < \( \alpha \) < 0.4 found in Figures 17 and 18 implies that there is, in fact, plenty of absorbing material between the AD and the dust grains. This means for the bowl model considered here, that even the line between the AD and the bowl edge at \( \theta \sim 45^\circ \) crosses a significant amount of absorbing material. The large H\( \alpha \) lag/dust lag mentioned in Section 5.1 may hint to such material.

(2) Geometric effects of a bowl mirror: We assume a bowl model with a fixed half-opening angle \( 45^\circ \) irrespective of the AD luminosity. Clearly, both the bowl rim and material inside the bowl act in the net effect like a reflecting mirror for the photons from the AD. The photons are scattered by electrons and dust grains. In addition, reprocessed continuum emission may play a role; for instance, Chelouche et al. (2019) found evidence of a non-disk optical continuum emission around AGNs, which likely comes from the inner wall of the BLR. Thus, the observer sees—in addition to the AD flux \( F_{\text{AD}} \)—a contribution \( F_{\text{bowl}} \) from scattered or reprocessed photons. This leads to an amplification of the original AD brightness. The relative amplification

\[
\text{Ampl} = F_{\text{bowl}}/F_{\text{AD}}
\]

may be small (a few percent), but it is worth considering the extent of its luminosity dependence. We make the assumption that the bowl opening angle and the geometric covering angle for intercepting AD photons is luminosity independent. Then, the effect of the bowl rim on \( \text{Ampl} \) might be scale-invariant. However, the volume inside the bowl increases proportional to \( R_{\text{bowl}}^3 \). If the density of scattering or reprocessing particles inside the bowl is independent of the AD luminosity, then one may expect that \( F_{\text{bowl}} \propto R_{\text{bowl}}^2 \). This yields \( \text{Ampl} \propto R_{\text{bowl}}^2 \). Assuming, for simplicity, that \( R_{\text{bowl}} \propto L^{1/2} \), we get \( \text{Ampl} \propto L^{1/2} \). In other words, in the net effect, the actual luminosity of the AD may be overestimated by a factor that scales with \( L^{1/2} \). Then, in the lag–luminosity relation, the data points will be shifted to large \( L \) values, so that the resulting slope becomes shallower than \( \alpha = 0.5 \).
A detailed quantitative consideration of the potential Strömgren-like behavior of AGNs and the geometric effects of a bowl mirror will be presented in a future paper.

6. Summary and Conclusions

We performed a 5 yr reverberation mapping campaign of 3C 273 in the optical (BVr) and NIR (JHK) bands at OCA. The optical light curves were supplemented by longer and denser sampled V-band light curves from Zhang et al. (2019). The results are as follows:

1. To obtain the pure dust light curves, the contributions of the host galaxy and accretion disk to the NIR bands had to be removed. The resulting dust light curves show consistently correlated variations in all three NIR bands, giving confidence that the procedure worked well to remove the contribution of host galaxy and accretion disk.

2. For all three filter pairs (J/H, J/K, H/K), the color temperatures change by about 5% (i.e., a factor 1.05) between the bright and faint states. On the other hand, the amplitudes of the dust light curves increase with decreasing wavelength from 0.2 at $K$ to 0.4 in J. Because the filters measure the dust emission on the Wien tail of the Planck function, the brightness changes are expected to become larger at shorter wavelengths; they may exceed the amplitude of the triggering signal light curve. Altogether, this consistently indicates that the variations of the dust emission are likely due to (mean) temperature changes of the dust grains of the order of 5%.

3. We derived the dust CF from the optical/UV and NIR luminosities, yielding small values, CF $\sim$ 8%, consistent with the results, CF $\sim$ 7%, for other type-1 AGNs by Landt et al. (2011).

4. We determined the time lag $\tau$ of the dust light curves against the V-band light curve through different CCF methods and found an average time lag of $\tau_{K,rest} \sim 410$ days. Some correlation methods reveal an interesting asymmetry, which is consistent with the TF of a tilted dust geometry.

5. We reanalyzed the data of Soldi et al. (2008) and compared the dust time lag and CCF asymmetries during our observing campaign and theirs.

6. The average time lag of $\tau_{rest} \sim 410$ days is a factor of $\sim 2$ smaller than that expected from the interferometric ring radius of $\sim 900$ lt-day. Interferometry measures the projected size as seen by the observer, while RM measures the three-dimensional light travel time difference in the system. We suggest that the difference between interferometric size and RM lags can be explained by 3D geometrical effects, in particular, the foreshortening effect from which the reverberation data suffer.

7. To bring the observational findings into a consistent picture, we considered a bowl-shaped torus geometry as proposed by Goad et al. (2012), where the dust emission originates from the edge of the bowl rim with a small covering angle $40^\circ < \theta < 45^\circ$, as justified by the small CF. We used an inclination angle of $12^\circ$ indicated from radio jet studies (Lobanov & Zensus 2001; Savolainen et al. 2006; Jorstad et al. 2017). For such a model with an equatorial size $R_e \sim 900$ lt-day the (simple geometric) TF is double-horned and yields an asymmetric cross correlation similar to that found from the data. We have convolved different TFs for a bowl geometry with the host-subtracted V-band light curve and showed the corresponding echo light curves. For an equatorial size $R_e \sim 900 \pm 200$ lt-day, the echo light-curve delays are in agreement with the delays found in our data, and the modeled cross correlations show an asymmetry similar to that observed in the CCF. The main conclusion from our study is that the hot dust emission seen in the NIR originates from a tilted ($i = 12^\circ$) thin ring that lies above the equatorial plane.

8. The relation between dust lag and optical luminosity shows a large scatter. To reduce the scatter for future cosmological applications, it may be desirable to obtain $R_e$ via modeling of the data (provided they are of sufficient quality) and check for a relation between $R_e$ and $L$.

9. We find, for the lag–luminosity relation, a rather shallow slope between 0.33 and 0.4. This rejects the widely adopted slope of 0.5 at the 3σ level. We envisage three possible explanations for this shallow slope:

(a) Gaskell et al. (2004) found that the internal extinction in AGNs increases with decreasing AGN luminosity by $A_V \sim 2.5$ mag between quasars and Seyferts. If the internal extinction in AGNs is, in fact, this high and shows such a strong luminosity dependence, then the slope may be tilted from 0.5 to about 0.33.

(b) AGNs have a similar behavior as H II regions where the size of the ionized region $R_{HI} \propto L^{1/3}$. If a substantial amount of absorbing material lies between the AD and the dust grains, this allows for a shortened dust sublimation radius. If the material density is $L$-invariant, the relative shortening increases with the path length between the AD and dust. The path length (bowel size) depends on $L$. Then, in the lag–luminosity diagram, the relative reduction of the lag increases with $L$.

(c) The observer measures an AD luminosity $L$, which is magnified by scattered and reprocessed radiation from material in the bowl, and the relative contribution of this magnification of $L$ increases with the volume of the bowl and, therefore, also with $L$. Then, in the lag–luminosity diagram, the relative overestimation of $L$ increases with $L$.

While these findings apply to the single case of the luminous quasar 3C 273, future detailed studies of a larger quasar sample should be envisaged to corroborate the conclusions.

This project was supported by funds from the Akademie der Wissenschaften Nordrhein-Westfalen and Deutsche Forschungsgemeinschaft HA3555/12 and HA3555/14. The observations benefited from the care of the guardians Hector Labra, Gerardo Pino, Roberto Muñoz, and Francisco Arraya. We warmly thank Jian-Min Wang and Zhi-Xiang Zhang for sending us their light curves of 3C 273, and we thank the referee Martin Gaskell for his detailed and constructive report.

Appendix

Different Cross-correlation Functions

Figure A1 presents the CCF (DCF, ICCF, ZDCF, and VNRM) between V and JHK dust light curves for this work and also for Soldi et al. (2008) data.

16
Figure A1. DCF, ICCF, ZDCF, and VNRM between $V$ and $JHK$ light curves for this work and Soldi et al. (2008).
