Reconciling the Quasar Microlensing Disk Size Problem with a Wind Model of Active Galactic Nucleus

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ABSTRACT

Many analyses have concluded that the accretion disk sizes measured from the microlensing variability of quasars are larger than the expectations from the standard thin disk theory by a factor of ~ 4. We propose a simply model by invoking a strong wind from the disk to flatten its radial temperature profile, which can then reconcile the size discrepancy problem. This wind model has been successfully applied to several microlensed quasars with a wind strength \( s \lesssim 1.3 \) by only considering the inward decreasing of the mass accretion rate (where \( s \) is defined through \( \dot{M}(R) \propto (R/R_0)^s \)). After further incorporating the angular momentum transferred by the wind, our model can resolve the disk size problem with an even lower wind parameter. The corrected disk sizes under the wind model are correlated with black hole masses with a slope in agreement with our modified thin disk model.

Keywords: accretion, accretion disks—black hole physics—ISM: jets and outflows—quasars: general—gravitational lensing: micro

1. INTRODUCTION

It is widely accepted that active galactic nuclei (AGNs) in the distant universe are powered by accretion disks around the supermassive black holes. The simple Shakura & Sunyaev (1973) thin-disk model (see also Novikov & Thorne 1973) remains the standard model for luminous AGNs due to its success in modeling some major features in observations (e.g., the “Big Blue Bump” in the spectral energy distribution of quasars). However, this simple model has shown some difficulties in some aspects, e.g., in explaining the soft X-ray continuum, optical polarization, and variability (Koratkar & Blaes 1999).

More remarkably, a “size problem” has been recently identified by many works. Based on the microlensing observations for quasars, the disk size can be measured from microlensing variabilities. We can also obtain two disk sizes based on the thin disk theory (see Equation 5) and the magnification-corrected flux (see Equation 6). These observations show that the disk sizes measured from microlensing variabilities are systematically larger than the thin-disk theory size by a factor of ~ 4 (e.g., Pooley et al. 2007; Dai et al. 2010; Morgan et al. 2010; Jiménez-Vicente et al. 2012; Blackburne et al. 2014; Muñoz et al. 2016; Motta et al. 2017). Several suggestions have been put forward to reduce the size discrepancy, e.g., scattering a significant fraction of the disk emission or including the line emission contamination from larger physical scales (Morgan et al. 2010), a flatter disk temperature profile because of some unknown reasons (Dai et al. 2010; Morgan et al. 2010; Bonning et al. 2013), or an inhomogeneous disk with large temperature fluctuations (Dexter & Agol 2011; Cai et al. 2018).

In this work, we propose that a thin disk with wind can flatten the temperature profile, which then can solve the disk size problem. This shares a similarity with the suggestion of a flatter disk temperature profile mentioned above, although the physical origin of the flattening has not been linked to disk winds in previous works yet. Observationally, a flattening of temperature profile than the theoretical expectation of \( 3/4 \) from the thin-disk model has been confirmed for several microlensing studies of disk structures (e.g., Bate et al. 2008; Poindexter et al. 2008)\(^1\). The effects of winds from thin disks on the spectral shape and black hole growth rate of AGNs have been discussed by Slone & Netzer (2012).

There is now compelling evidence for the existence of wind in different types of accretion flows both observationally and theoretically. For the hot accretion flow, both hydrodynamic (HD) and magnetohydrodynamic (MHD) numerical simulations have found that the mass inflow rate decreases with decreasing radius with a wind strength \( s \sim 0.5 \) (see the definition of \( s \) in Equation (1); e.g., Stone et al. 1999; Yuan et al. 2012b, see review by Yuan & Narayan 2014). Yuan et al. (2012a) show that the inward decrease of the ac-

\(^1\) A few sources show that the temperature profile could be even steeper than \( 3/4 \), although the uncertainty is large (e.g., Eigenbrod et al. 2008; Muñoz et al. 2016).
cretion rate is attributed to the significant mass loss through wind (see also Narayan et al. 2012; Gu 2015; Yuan et al. 2015). This result is confirmed later by Chandra observations for the supermassive black hole in our Galaxy (Wang et al. 2013). For the standard thin disk powering luminous quasars, numerous pieces of observational evidence have been accumulated via studies of broad absorption/emission line quasars (e.g., Arav et al. 2001; Chartas et al. 2003; Crenshaw et al. 2003; Dai et al. 2008, 2012; Tombesi et al. 2014; Gofford et al. 2015; King & Pounds 2015; Liu et al. 2015; Sun et al. 2018a). These winds can be launched by thermal, radiation, and/or magnetic mechanisms (e.g., Proga 2003; Nomura & Ohsuga 2017; Waters & Proga 2018; Wang et al. 2018, in preparation).

The paper is organized as follows. Our wind model is described in details in Section 2, and the influence of the angular momentum transfer by wind is further discussed in Section 3. We apply our wind model to several microlensed quasars in Section 4. The final section is devoted to a summary of this work.

2. A PHENOMENOLOGICAL WIND MODEL

We adopt a phenomenological model to describe the mass accretion rate profile \( \dot{M}(R) \) of the disk suffering from a wind

\[
\dot{M}(R) = \dot{M}_{\text{in}} \left( \frac{R}{R_0} \right)^s, \quad R \geq R_0, \tag{1}
\]

where \( \dot{M}_{\text{in}} \) is the mass accretion rate at \( R_0 \) and \( R_0 \) is chosen as the inner edge of the disk where wind can dominate over inflow. The wind parameter \( s \) is kept as constant in the disk, and the no wind special case is at \( s = 0 \). Numerical simulations and theoretical works for the hot accretion flows suggested that \( R_0 \simeq 20 - 40 R_g \) (Yuan et al. 2012a; Narayan et al. 2012; Yuan et al. 2015; Ma et al. 2018, in preparation), where \( R_g = GM_{\text{BH}}/c^2 \) is the gravitational radius of a black hole, \( c \) is the speed of light, and \( M_{\text{BH}} \) is the black hole mass. However, different wind production mechanisms for the thin disk can result in different \( R_0 \). Since we do not have theoretical or observational constraints on \( R_0 \) for the thin disk, we adopt \( R_0 = 6 R_g \) in this work, which is the innermost stable circular orbit for a Schwarzschild black hole.

With the radius-dependent mass accretion rate, the effective temperature profile \( T(R) \) for a thermally radiating black body disk can be obtained by

\[
\frac{3GM_{\text{BH}}\dot{M}(R)}{8\pi R^3} = \sigma T^4(R), \tag{2}
\]

which leads to \( T(R) \propto R^{-\beta} \) with \( \beta = (3-s)/4 \), where \( \sigma \) is the Stefan-Boltzmann constant. The resulting surface brightness at a rest wavelength \( \lambda_0 \) is given by

\[
f_\nu = \frac{2h_\nu c}{\lambda_0^3} \left[ \exp \left( \frac{R}{R_{\lambda_0}} \right)^\beta - 1 \right]^{-1}, \tag{3}
\]

where the scale length \( R_{\lambda_0} \) characterized by \( kT(R) = h_\nu c/\lambda_0 \) defines the theory size of the disk,

\[
R_{\lambda_0,\text{th}}(\beta) = \left[ \frac{4G\lambda_0^2M_{\text{BH}}\dot{M}_{\text{in}}}{16\pi^6h_\nu c^2R_0^4} \right]^{1/(3-s)} \tag{4}
\]

The size scales with the wavelength \( \lambda \) as \( R_{\lambda,\text{th}} \propto \lambda^{1/\beta} \). Here \( G \) is the gravitational constant, \( h_\nu \) is the Planck constant, and \( k \) is the Boltzmann constant. Assuming a luminosity \( L = \eta M_{\text{in}}c^2 \) and an Eddington ratio of \( L/L_{\text{Edd}} = f \), where \( \eta \) is the radiative efficiency, and \( L_{\text{Edd}} \) is the Eddington luminosity, we can rewrite Equation (4) as

\[
R_{\lambda_0,\text{th}}(\beta) = \left[ \frac{45fG^2m_p\lambda_0^4M_{\text{BH}}^2}{4\eta\pi^5hc^3\sigma T R_0^4} \right]^{1/(3-s)}, \tag{5}
\]

where \( \sigma_T \) is the Thomson cross-section, \( m_p \) is the mass of a proton. We adopt a typical Eddington ratio \( f = 0.1 \) for quasars (Shen et al. 2008), although Kollmeier et al. (2006) estimate a slightly larger value of \( f \simeq 1/4 \). The dependence of \( R_{\lambda_0,\text{th}} \) on the black hole mass \( M_{\text{BH}} \) is modified as \( R_{\lambda_0,\text{th}} \propto M_{\text{BH}}^{(2-s)/(3-s)} \), which recovers to the predicted slope of \( 2/3 \) from the thin-disk theory in the case of the no-wind model (i.e., \( s = 0 \)).

Under the same model assumption, we can obtain another disk size by setting the integrated surface brightness profile over the whole disk with the magnification-corrected quasar fluxes at a given band. The flux size under the wind model is then given by

\[
R_{\lambda_0,\text{flux}}(\beta) = \frac{D_{\text{OS}}}{4\pi h_\nu c \cos i} \sqrt{\frac{K(3/4)}{K(\beta)}} \frac{\lambda_0^{3/2} F_{\nu}^{1/2}}{R_{\text{H}}} \\
= \frac{2.8 \times 10^{15}}{h \sqrt{K(\beta)/K(3/4) \cos i}} \frac{D_{\text{OS}}}{R_{\text{H}}} \left( \frac{\lambda_0}{\mu\text{m}} \right)^{3/2} \\
\times \left( \frac{z_{\text{pt}}}{2409 \text{ Jy}} \right)^{1/2} \times 10^{-0.2(m-19)} \text{ cm}, \tag{6}
\]

where \( i \) is the inclination angle of the disk, \( m \) is the magnification-corrected magnitude for microlensing sources, \( D_{\text{OS}}/R_{\text{H}} \) is the source angular distance in units of the Hubble radius \( R_{\text{H}} \equiv c/H_0 \), \( h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and for \( kT(R_{\text{stat}})/h \ll c/\lambda_0 \ll kT(R_0)/h \),

\[
K(\beta) = \int_0^\infty \left[ \exp(x^\beta) - 1 \right]^{-1} x \, dx. \tag{7}
\]

It clearly shows that the flux size of the disk \( R_{\lambda_0,\text{flux}} \) depends on the temperature profile via the wind parameter \( s = 3 - 4\beta \). For the no-wind model, \( K(\beta = 3/4) = 2.58 \). The dependence of \( K \) on the wind strength \( s \) is shown in Figure 1, which implies that \( R_{\lambda_0,\text{flux}} \) decreases significantly with the wind strength.
For the disk-size measurement via microlensing variability, it is the half-light radius of the gravitationally lensed quasars that is measured. Based on the wind-corrected surface brightness profile in Equation (3), we can relate the half-light radius of the disk \( R_{\lambda_0, \text{half}} \) with the scale size \( R_{\lambda_0} \) in Equation (3) as

\[
R_{\lambda_0, \text{half}}(\beta) = C(\beta)R_{\lambda_0, \text{mic}}(\beta),
\]

where \( C(\beta) \) is the conversion factor from \( R_{\lambda_0} \) in Equation (3) to \( R_{\lambda_0, \text{half}} \). Here \( R_{\lambda_0} \) is labeled as the third disk size, namely the microlensing size \( R_{\lambda_0, \text{mic}} \), which can be directly compared with other disk size measurements. \( C(\beta) \) is defined as

\[
C(\beta) = \mathcal{F}^{-1}\left[\frac{1}{2}K(\beta)\right],
\]

where \( \mathcal{F}^{-1}(\cdot) \) is the inverse function of

\[
\mathcal{F}(x) = \int_0^x \left[\exp(u^\beta) - 1\right]^{-1}udu.
\]

Under the no-wind circumstance, i.e., \( \beta = 3/4 \), \( C(3/4) = 2.44 \). We also plot the profile of \( C \) as a function of the wind parameter \( s \) in Figure 1. The half-light radius measured from microlensing is nearly model independent (Mortonson et al. 2005; Congdon et al. 2007), so a different wind strength can modify the disk size \( R_{\lambda_0, \text{mic}} \) as well.

Theoretically speaking, the three disk sizes \( R_{\lambda_0, \text{th}} \), \( R_{\lambda_0, \text{flux}} \) and \( R_{\lambda_0, \text{mic}} \) defined in Equations (5,6,8), respectively, should be consistent with each other. However, there are striking discrepancies among these three size measurements observationally. Even though the offset between the microlensing size measurements and flux size (Equation 5) tends to be somewhat smaller, which can be attributed by other uncertainties (e.g., radiative efficiency \( \eta \), and Eddington ratio \( f \)), the discrepancy between the microlensing size (Equation 8) and the expectation from the flux measurement (Equation 6) is more significant in most microlensed quasars with the former being larger than the latter by 0.6 ± 0.3 dex (e.g., Pooley et al. 2007; Poindexter et al. 2008; Morgan et al. 2010, 2012).

We mainly focus on the major size problem arisen from the discrepancy between the flux size \( R_{\lambda_0, \text{flux}} \) and the microlensing one \( R_{\lambda_0, \text{mic}} \). As both \( R_{\lambda_0, \text{flux}} \) and \( R_{\lambda_0, \text{mic}} \) are sensitive to the wind parameter \( s \), the correction factor of the size ratio due to the disk wind based on Equations (6) and (8) can be described by

\[
\Delta(\frac{R_{\text{flux}}}{R_{\text{mic}}}) = \sqrt{\frac{K(3/4)}{K(\beta)}} \times \frac{C(\beta)}{C(3/4)}.
\]

which is shown as the solid line in Figure 2. It clearly demonstrates that the flux to microlensing size ratio correction can be a factor of \( \sim 3 \) as the wind parameter increases to \( \sim 1.3 \). It, therefore, indicates that a disk model with a strong wind can potentially resolve the underestimation of flux size measurements up to 0.6 dex.

### 3. Influence of Angular Momentum Transfer by Wind

While our phenomenological treatment of the wind described by Equation 1 is the standard treatment in most previous works, wind could play another role in modifying the inflow by transferring the angular momentum outward. This has been studied for two types of disk models.
& Yuan (2008) have investigated this problem in details for the advection-dominated accretion flow by incorporating the interchange of mass, momentum, and energy between the inflow and outflow. They confirm that the phenomenological treatment of wind is reasonable for the hot accretion flow. For the thin disk, Kuncic & Bicknell (2007) proposed a phenomenological model by including the vertical angular momentum transfer induced by the wind. This provides a straightforward way to be compared with our wind model.

For the purpose of reconciling the disk size discrepancy, it is related with the modification of the radial temperature profile of the disk determined by the radiative flux, which is required to balance with the viscous dissipation rate. The radiative flux of a thin disk after the consideration of the angular momentum transferred by the wind can be expressed as (Kuncic & Bicknell 2007)

\[ F_\nu(R) = \frac{3GM_{BH}\dot{M}(R)}{8\pi R^3} \xi_{corr}(R). \]  

(11)

The additional radial-dependent correction factor \( \xi_{corr}(R) \) is given by

\[ \xi_{corr}(R) = 1 - \left( \frac{R}{R_0} \right)^{-\frac{3}{2} - s} - \frac{1 + 2s - 2w}{1 + 2s - 2w} \times \left( \frac{R}{R_0} \right)^{-w} \left[ 1 - \left( \frac{R}{R_0} \right)^{-\frac{3}{2} - s + w} \right], \]

(12)

where \( w \) is another parameter describing the radial dependence of the angular momentum transfer by the wind (Kuncic & Bicknell 2007). A smaller \( w \) indicates a stronger effect of angular momentum transportation by wind. There exists no observational and theoretical constraints for this parameter, which makes a detailed quantitative assessment of this effect difficult. However, we can qualitatively discuss this effect in the disk temperature profile.

We show the radial profile of \( \xi_{corr}(R) \) for different combinations of \( s \) and \( w \) parameters in Figure 3. Since the effective temperature is determined by \( T(R) \sim F_\nu^{1/4}(R) \), a steep positive radial gradient of \( \xi_{corr}(R) \) can be obtained in a large radial range of the disk, which in turn results in an even flatter temperature profile. Furthermore, the slope becomes steeper in the inner regions of the disk. This is equivalent to a larger effective wind parameter \( s_{eff} \) in the inner region. Therefore, it can help to resolve the disk size problem with a relatively small wind parameter.

4. APPLICATION TO MICROLENSED QUASARS

We first apply our wind model to several gravitationally microlensed quasars without considering the angular momentum transfer effect. Morgan et al. (2010) have collected 11 quasars with their microlensing size and flux size reported. We select 9 sources from their samples as shown in Table 1, except that HE 0435–1223 and PG 1115+080 are excluded since their size discrepancies are too large to be explained by our model.

To reconcile between the flux and microlensing size measurements, one can make the observational size ratio \( R_{mic,obs}/R_{flux,obs} \) be linked to the correction factor defined in Equation (10). The observational size ratios and the \( 1\sigma \) uncertainties for all sources can be obtained through a Monte Carlo sampling of \( R_{flux,obs} \) and \( R_{mic,obs} \) as listed in Table 1. By setting \( R_{mic,obs}/R_{flux,obs} = \Delta (R_{flux}/R_{mic}) \), we can obtain the required wind parameters, which are shown in Figure 2 and listed in Table 1. It indicates that the underestimation of the flux size can be well explained with a wind strength \( s \sim 1 \) for our sources. The typical uncertainty of \( s \) is relatively large (~0.5), which can be estimated from the uncertainty of \( R_{mic,obs}/R_{flux,obs} \) shown in Figure 2. In addition, the required \( s \) values can be decreased by \( \sim 0.1 \) if considering the inner edge effect in Equations (7) and (9). It is thus still possible to interpret the size discrepancy with a wind strength \( s < 1.0 \) after considering this uncertainty.

Observationally, the wind parameter \( s \) for the thin disk has not been well constrained up to date. There are some constraints for the hot accretion flow in several low-luminosity AGNs [e.g., \( s \sim 0.5 \) for M87 (Russell et al. 2015) and NGC 3115 (Wong et al. 2014)] and Sagittarius A* (\( s \sim 1.0 \); Wang et al. 2013) by X-ray observations. Numerical simulations of hot accretion flows show that \( s \sim 0.5 – 1.0 \) (see review by Yuan & Narayan 2014 and references in the Introduction.).

More importantly, the required wind parameter to interpret the size discrepancy can be reduced by \( \sim 0.5 \) if the angular momentum transfer effect by the wind is considered, as estimated from Figure 3. This can make the required \( s < 1.0 \) (e.g., FBQ 0951+2635, HE 1104–1805) and relieve the disk size problem for some sources, e.g., HE 0435–1223 and PG 1115+080.
TABLE 1. Sources parameters and corrected disk sizes

| Objects          | $M_{\text{BH}}$ ($10^9 M_\odot$) | $\lambda_0$ (\mu m) | $\log(R_{\text{mic,obs}}/\text{cm})$ | $\log(R_{\text{flux,obs}}/\text{cm})$ | $s$ | $\log(R_{\text{corr, mic}}/\text{cm})$ | $\log(R_{\text{corr}}/\text{cm})$ |
|------------------|----------------------------------|----------------------|----------------------------------------|----------------------------------------|-----|----------------------------------------|----------------------------------------|
| QJ 0158–4325     | 0.16                             | 0.310                | 15.6±0.3                               | 15.2±0.1                               | 1.1 | 14.7±0.3                               | 14.9                                    |
| SDSS 0924+0219   | 0.11                             | 0.277                | 15.0±0.3                               | 14.8±0.1                               | 0.6 | 14.6±0.4                               | 14.7                                    |
| FBQ 0951+2635    | 0.89                             | 0.313                | 16.1±0.4                               | 15.6±0.1                               | 1.3 | 14.9±0.4                               | 15.3                                    |
| SDSS 1004+4112   | 0.39                             | 0.228                | 14.9±0.3                               | 14.9±0.2                               | 0.02| 14.9±0.3                               | 14.9                                    |
| HE 1104–1805     | 2.37                             | 0.211                | 15.9±0.2                               | 15.4±0.1                               | 1.3 | 14.9±0.3                               | 15.5                                    |
| RXJ 1131–1231    | 0.06                             | 0.400                | 15.2±0.2                               | 14.8±0.1                               | 1.0 | 14.2±0.2                               | 14.7                                    |
| SDSS 1138+0314   | 0.04                             | 0.203                | 14.9±0.6                               | 14.6±0.1                               | 0.9 | 14.4±0.6                               | 14.5                                    |
| SBS 1520+530     | 0.88                             | 0.245                | 15.7±0.2                               | 15.3±0.1                               | 1.1 | 14.9±0.2                               | 15.3                                    |
| Q2237+030        | 0.90                             | 0.208                | 15.6±0.3                               | 15.5±0.2                               | 0.3 | 15.5±0.3                               | 15.2                                    |

Note—Data are collected from Morgan et al. (2010), except for QJ 0158–4325 (Morgan et al. 2012) and RXJ 1131–1231 (Dai et al. 2010). $R_{\text{flux, obs}}$ and $R_{\text{mic, obs}}$ are disk sizes in the no-wind model. The typical uncertainty of inferred $s$ is $\sim 0.5$, as seen from Figure 2. $R_{\text{corr, mic}}$ is the corrected flux/microlensing size after the correction based on our wind model measured at 0.25 \mu m. The 1\sigma errors of $R_{\text{corr, mic}}$ are obtained by 5000 Monte Carlo sampling. $R_{\text{corr}}$ is the wind-modified theory disk size with $\eta = 0.1$ and $f = 0.1$ at 0.25 \mu m (Equation 5). The typical uncertainty of $R_{\text{corr}}$ is $\sim 0.1$ dex.

1115+080. Considering these complexities, we think that the wind parameters $s$ as shown in Figure 2 are in the reasonable range.

With the inferred wind parameters, we can calculate the wind-corrected disk sizes. Note that the flux and microlensing sizes are already consistent with each other by definition. We show the wind-corrected flux (or microlensing) size $R_{\text{corr}}^\text{mic}$ at 0.25 \mu m as a function of the black mass $M_{\text{BH}}$ as black squares in Figure 4. The 1\sigma uncertainties of the modified microlensing sizes are obtained via Monte Carlo simulations as well. The typical black hole mass uncertainty is 0.1 dex. A Markov Chain Monte Carlo method (Lewis & Bridle 2002; Li et al. 2015) is applied to fit the correlation between $R_{\text{corr}}^\text{mic}$ and $M_{\text{BH}}$ by including the uncertainties for both variables yielding

$$\log \left( \frac{R_{\text{corr}}^\text{mic}}{\text{cm}} \right) = (9.91 \pm 1.45) + (0.56 \pm 0.17) \log \left( \frac{M_{\text{BH}}}{M_\odot} \right).$$

(13)

The corresponding best fit and 1\sigma error band are shown as solid and dashed blue lines, respectively, with the best-fitted statistics $\chi^2_d = 6.0/7 \approx 0.9$, suggesting a reasonable fit to the data.

By assuming a typical radiative efficiency of $\eta = 0.1$ and Eddington ratio $f = 0.1$ for all sources, the wind-corrected thin-disk theory sizes $R_{\text{corr}}^\text{th}$ as defined in Equation (5) can be obtained, which are represented as grey circles in Figure 4. Assuming an uncertainty of 0.1 dex for both $R_{\text{corr}}^\text{mic}$ and $M_{\text{BH}}$, a power-law function is applied to fit between $R_{\text{corr}}^\text{mic}$ and $M_{\text{BH}}$, which leads to

$$\log \left( \frac{R_{\text{corr}}^\text{th}}{\text{cm}} \right) = (10.4 \pm 0.6) + (0.55 \pm 0.07) \log \left( \frac{M_{\text{BH}}}{M_\odot} \right).$$

(14)

The fitted power law is shown as the grey line in Figure 4 with $\chi^2_d = 4.6/7 \approx 0.7$, suggesting a slightly overestimate of uncertainties for $R_{\text{corr}}^\text{th}$. The power-law function in Equations (13) and (14) are roughly consistent with each other after considering the 1\sigma uncertainties, suggesting that the three

![Figure 4. Wind-corrected disk size at 0.25 \mu m as a function of black hole mass $M_{\text{BH}}$. The black squares with error bars are flux sizes, which have been corrected to match the microlensing sizes. The solid blue line shows the fit to the corrected flux size VS. black hole mass with the dashed blue lines representing the 1\sigma uncertainty. The grey circles show the wind-corrected theory sizes from Equation (5) with a radiative efficiency of 0.1. The grey line represents the fit to the theory size. The dotted line shows the gravitational radius $R_\text{g}$ of the black hole.](image-url)
disk sizes can now be in agreement with each other within the framework of our wind model. We can also judge the consistency between $R_{\text{th}}^{\text{corr}}$ and $R_{\text{mic}}^{\text{corr}}$ by calculating $\chi^2_{\nu}$ between these two disk sizes, which gives $\chi^2_{\nu} \approx 1.7$. The slightly large $\chi^2_{\nu}$ is mainly contributed by two sources, RXJ 1131−1231 and HE 1104−1805. If these two sources are excluded from the test above, we obtain $\chi^2_{\nu} \approx 0.9$, confirming a general consistency between these disk sizes after corrected by the wind.

After considering the angular momentum transfer effect as discussed in Section 3, which reduces the wind parameter $s$ required, these two sizes will further shift toward each other (e.g., RXJ 1131−1231). In addition, a slightly higher radiative efficiency (e.g., $\eta \approx 0.15$) can also make $R_{\text{th}}^{\text{corr}}$ closer to $R_{\text{flux}}^{\text{corr}}$. The power-law index in Equation (14) favors a slightly flatter correlation slope, consistent with a wind parameter $s > 0$ as suggested by Equation (5).

Interestingly, as the above consistency is based on an assumption of radiative efficiency $\eta = 0.1$, it implies the reasonability of a canonical value $\eta = 0.1$ expected from the thin disk theory (Frank et al. 2002), higher than those estimated from Morgan et al. (2010). This is because the radiative efficiency should become higher to produce the same flux with a smaller corrected disk size.

As shown in Figure 4, the corrected disk sizes are $\sim 10 - 50 R_g$. These sizes are increased by a factor of $\sim 10$ on average when converting them into the half-light radius. This suggests that the emission extends to a more diffuse region. It simply lies in the fact that the radial temperature profile $T(R) \propto R^{-\beta}$ becomes flatter due to the existence of wind.

5. CONCLUSIONS

In this work, we propose a simple “wind” scenario to resolve the “size problem” for several microlensed quasars. With a wind strength $s \lesssim 1.3$ (where $s$ is defined via $\bar{M}(R) \propto (R/R_0)^{\beta}$), the temperature profile of the disk becomes much shallower. Our model can thus make three disk sizes, i.e., microlensing size, flux size, and theory size be consistent with each other. In addition to the mass flux carried away by the disk wind, the angular momentum transferred by the wind can further help to relieve the observational size mismatch with a smaller wind parameter.

In the meanwhile, the correlation between wind-corrected disk size and black hole mass becomes slightly flatter, which is in agreement with the theoretical expectation from a thin disk suffering from strong wind. With the updated disk size, we find that the radiative efficiency is close to the canonical value of 0.1 due to a smaller corrected flux size.

Due to the universality of wind in different accretion systems, the microlensing disk size measurements can thus provide a new probe for the wind properties in the inner region of quasars.

Upon the completion of this work, we notice that Sun et al. (2018, in preparation) propose a disk wind model focusing on resolving the inter-band time lag and spectral energy distribution for NGC 5548.

We are grateful to Yaling Jin for her contributions to this project. This work is supported in part by the National Key Research and Development Program of China (Grant No. 2016YFA0400704), the Natural Science Foundation of China (grants 11573051, 11633006, 11703064, 11650110427, 11661161012), the Key Research Program of Frontier Sciences of CAS (No. QYZDJSSW-SYS008), and Shanghai Sailing Program (grant No. 17YF1422600). This work made use of the High Performance Computing Resource in the Core Facility for Advanced Research Computing at Shanghai Astronomical Observatory and LANL Institutional Computing.

Software: CosmoMC (Lewis & Bridle 2002)

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