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The Correlation between Optical Spectral Index and Continuum Luminosity Variation in the Seyfert 1 Galaxy NGC 5548 *

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Abstract Using the archived optical spectra of NGC 5548 between 1989 and 2001, we derived the optical spectral index by fitting the spectra in wavelength windows unaffected by strong emission lines. We found that the index is anti-correlated with the continuum luminosity at 5100 Å with a correlation coefficient of −0.8. Based on the standard thin accretion disk model, we investigated whether the correlation is related to the variations of the dimensionless accretion rate $\dot{m}$ (mass accretion rate in Eddington unit), or the inner radius of the accretion disk $R_{\rm in}$, or both. The correlation can be modeled well using a co-variable mode of $R_{\rm in}/R_{\rm s} = 12.5\dot{m}^{-0.8}$ ($R_{\rm s}$ is Schwarzschild radius). As luminosity increases, $\dot{m}$ increases from 0.05 to 0.16 and at the same time $R_{\rm in}$ decreases from $133.9R_{\rm s}$ to $55.5R_{\rm s}$, consistent with the prediction for a transition radius within which an ADAF structure exists. We concluded that the change of both inner accretion radius and the dimensionless accretion rate are key factors for the variations of spectral index and luminosity in the optical band for NGC 5548.

Key words: accretion: accretion disks - black hole physics - galaxies: individual (NGC 5548)

1 INTRODUCTION

Variability of AGNs on different timescales is a common phenomenon throughout their electro-magnetic spectra. NGC 5548 is a low-redshift, bright Seyfert 1 galaxy which has been intensively observed in radio (Wrobel 2000; Wilson & Ulvestad 1982), optical (Peterson et al. 1991, 1994, 1999, 2002; Korista et al. 1995), UV (Clavel et al. 1991) and X-ray (Uttely et al. 2002). It varies in all bands. Moreover, the flux variations in the UV, optical and X-ray bands have been found to be correlated (Clavel et al. 1992; Uttely et al. 2003).

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The accretion of material to a central supermassive black hole has been thought to be the main mechanism to power an AGN. In order to explain the correlation of the flux variations in X-ray and optical bands, Chiang (2002) and Chiang & Blaes (2003) have presented a reprocessing model (Zdziarski et al. 1999) which includes a stationary thin accretion disk surrounding a thick hot central Comptonizing region. In this model, optical/UV flux variabilities are caused by changes of both the X-ray flux and the inner radius of the accretion disk. Using the data simultaneously observed in optical, UV and X-ray bands, Chiang (2002) and Chiang & Blaes (2003) estimated the accretion rate, the radius of the transition region and the black hole mass of NGC 5548. The mass is about $2 \times 10^7\,M_\odot$, much less than the $12.3 \times 10^7\,M_\odot$ estimated from the reverbration mapping method (Kaspi et al. 2000; Wandel et al. 1999). It is generally believed that the optical emission of Seyfert 1 galaxies is thermal emission from a cold optically thick accretion disk. The reprocessing model can explain the correlation between the optical and X-ray variations of NGC 5548, but can not explain why the amplitude of the variation is larger in the optical than in the X-ray (Uttley et al. 2003; Magdziarz et al. 1998). The physical reason for the variability and the correlation is still unclear. It may be related to the geometrical changes of the region emitting those continua, or to a variable transition region between a cold and hot disk or to a change of the inner disk radius (Magdziarz et al. 1998).

Using the data in a sample of 42 PG quasars, Trevese & Vagnetti (2002) found that a change of the accretion rate is not sufficient to explain the spectral slope variations in the optical band, while instabilities of the accretion disk may explain the observations (Kawaguchi et al. 1998). The correlation between the spectral index and luminosity can result from changes in the radiation temperature of the emitting blackbody. The spectral index can increase with the monochromatic luminosity at a given rest-frame frequency (Trevese et al. 2001).

We obtained the optical flux and spectral index of NGC 5548 using available archive data. We also found a correlation between the optical spectral index and the continuum flux at 5100 Å, and tried to explain the correlation by an accretion disk model.

2 SPECTRA AND DATA REDUCTION

NGC 5548 has been extensively monitored in the optical band by the International AGN Watch program (Peterson et al. 1991, 1992, 1994, 1999, 2002; Dietrich et al. 1993; Korista et al. 1995; Wanders et al. 1996). The data of optical continuum and emission line fluxes are available on the website (http://www-astronomy.mps.ohio-state.edu/˜agnwatch/). We obtained optical spectra of NGC 5548 between 1989 and 2001 from the International AGN Watch public archive.

We used spectra in the range from about 4000 Å to 6000 Å or broader to derive the continuum spectral index in such regions that are known to be relatively unaffected by strong emission lines, especially, the Fe II lines, 3700–3715 Å, 3740–3800 Å, 4041–4043 Å, 4150–4250 Å, 5550–5850 Å, 6000–6290 Å and 6400–6450 Å. After checking the signal-to-noise ratio of the spectrum, the wavelength coverage, and the response function at the blue and red regions of the spectrum, we finally selected 431 spectra for our analysis.

The data of optical continuum flux at 5100 Å (at rest frame) were also obtained from the AGN Watch Data Archive. Considering the differences in the resolution and wavelength scales among the various spectra, the data are scaled to a constant flux of [O III]λ 5007 Å using the automatic scaling algorithm provided by Van & Wanders (1992). The results are further corrected for the systematic difference between the different telescopes. Other corrections made include the host galaxy contribution, the Galactic extinctions (Howarth 1983) and Doppler effects. The host galaxy contribution at 5100 Å is about 3.4×10^{-15} erg s^{-1} cm^{-2} Å^{-1} (Romainishin et al. 1995). The value of $E(B-V)$ and redshift were taken from the NED database (http://nedwww.ipac.caltech.edu/) which are 0.020 and 0.01717, respectively.

The spectral index α, defined as $f_\lambda \propto \lambda^{-2+\alpha}$, was obtained by a power-law fitting to each spectrum after these corrections have been done. The effect of the host galaxy on the spectral index is assumed to be small because of the narrowness of spectral wavelength coverage and the weakness of the contribution to the optical continuum at small aperture. We calculated λL_λ, the monochromatic luminosity at 5100 Å on adopting the following cosmological parameters: $q_0 = 0.5$, and $H_0 = 75$ km s^{-1} Mpc^{-1}.

3 RESULTS AND ACCRETION DISK MODELING

3.1 The Correlation between $\alpha_{\rm opt}$ and Monochromatic Luminosity at 5100 Å

Figure 1 shows the correlation between the optical spectral index $\alpha_{\rm opt}$ and the monochromatic continuum luminosity at 5100 Å from 431 spectra. The correlation coefficient is about -0.8. The index $\alpha_{\rm opt}$ obviously decreases as the monochromatic continuum luminosity at 5100 Å increases. This means the AGN has a flatter optical continuum spectrum when it is very bright, and has a steeper spectrum when it is less bright.

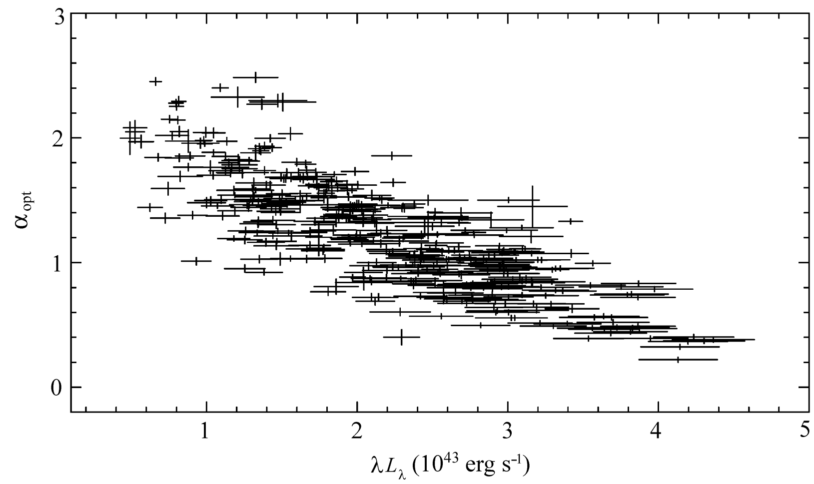

Fig. 1 Correlation between the optical spectral index $\alpha_{\rm opt}$ and the optical monochromatic continuum luminosity λL_λ at 5100 Å. The correlation coefficient is -0.8.

3.2 Interpretation with the Standard Thin Accretion Disk Model

The physical reason for the optical variability of AGNs is not clear at present. The reprocessing model by Chiang (2002) and Chiang & Blaes (2001, 2003) can not explain the larger amplitude of the optical light curves of NGC 5548 as compared to its X-ray light curves. On the other hand, the standard disk-corona model has the same difficulty in explaining the relation between the optical and X-ray variabilities (Beloborodov 1999). Possible mechanism may include thermal instability in the inner disk (Treves et al. 1988), or variation of the accretion rate of accretion disk, or both.

As our first attempt, we assume that the optical emission is mainly produced by a standard accretion disk, which is geometrically thin but optically thick (Shakura & Sunyaev 1973). In such a scenario, blackbody emission arises from every radius of accretion disk with a certain temperature (Frank et al. 1992), defined by

$$T(r) = \left[\frac{3GM\dot{M}}{8\pi\sigma r^3}\left\{1-\left(\frac{3R_{\rm s}}{r}\right)^{\frac{1}{2}}\right\}\right]^{\frac{1}{4}}, \tag{1}$$

where σ is the Stefan-Boltzmann constant and the local blackbody emission is given by

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{{\rm e}^{\frac{h\nu}{kT(r)}}-1}. \tag{2}$$

The total specific luminosity of the disk can then be obtained by an integration over the range from $R_{\rm in}$ to $R_{\rm out}$

$$L_\nu = \frac{4\pi^2 h\nu^3 \cos i}{c^2}\int_{R_{\rm in}}^{R_{\rm out}}\frac{r{\rm d}r}{e^{\frac{h\nu}{kT(r)}}-1}, \tag{3}$$

where i is the inclination of the disk to the line of sight, and we adopted its value of 45° (Chiang & Blaes 2003; Wu & Han 2001; Zhang & Wu 2002). We assume that the accretion flow inside $R_{\rm in}$ makes no contribution to the radiation. The black hole mass of NGC 5548 is taken to be $12.3 \times 10^7\,{\rm M}_\odot$ (Kaspi et al. 2000).

To investigate how the luminosity changes with the accretion rate and the inner radius of accretion disk, we tried the different relations between the continuum luminosity at 5100 Å and $\alpha_{\rm opt}$, as shown in Figs.2–4.

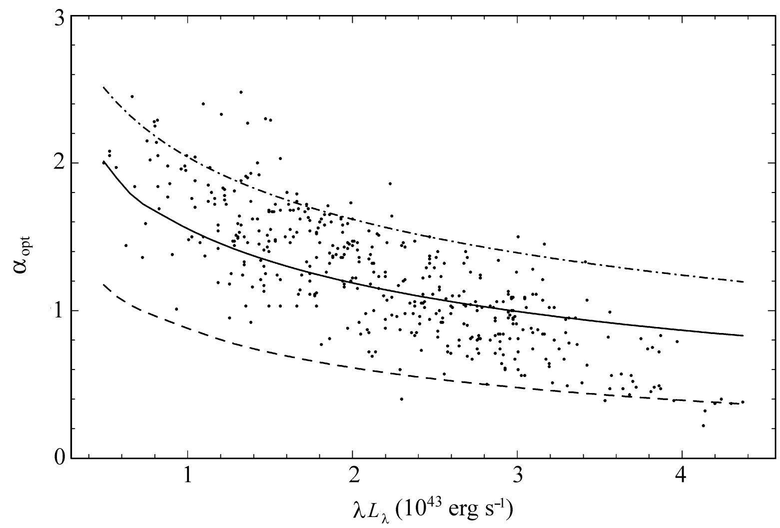

Fig. 2 Correlation between optical spectral index and the optical continuum luminosity at 5100 Å (rest frame) is fitted for three certain inner radii at $R_{\rm in} = 42\,R_{\rm s}, 82\,R_{\rm s}$ and $122\,R_{\rm s}$ from the bottom to the top. The curve is drawn for different dimensionless accretion rate $\dot{m}$ range. It is $0.012 \sim 0.133$ for dashed line, $0.026 \sim 0.205$ for solid line and $0.045 \sim 0.293$ for dot-dashed line.

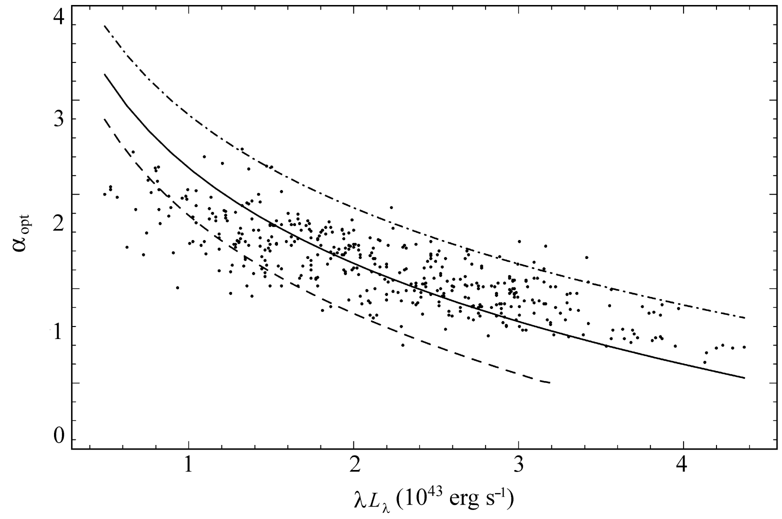

Fig. 3 Correlation of optical spectral index and the optical continuum luminosity at 5100 Å (rest frame) can also be fitted by a simple standard thin accretion disk model with a fixed dimensionless accretion rate $\dot{m}$. Three lines represent $\dot{m} = 0.06, 0.1$ and 0.18 from the bottom the top. The curve is drawn for variable inner accretion radius, which decreases with increases of the luminosity at 5100 Å from $148.5R_{\rm s}$ to $3R_{\rm s}$ for $\dot{m} \sim 0.06$ (dashed line), from $205.1R_{\rm s}$ to $19.6R_{\rm s}$ for $\dot{m} \sim 0.1$ (solid line) and from $288.0R_{\rm s}$ to $69.0R_{\rm s}$ for $\dot{m} \sim 0.18$ (dot-dashed line).

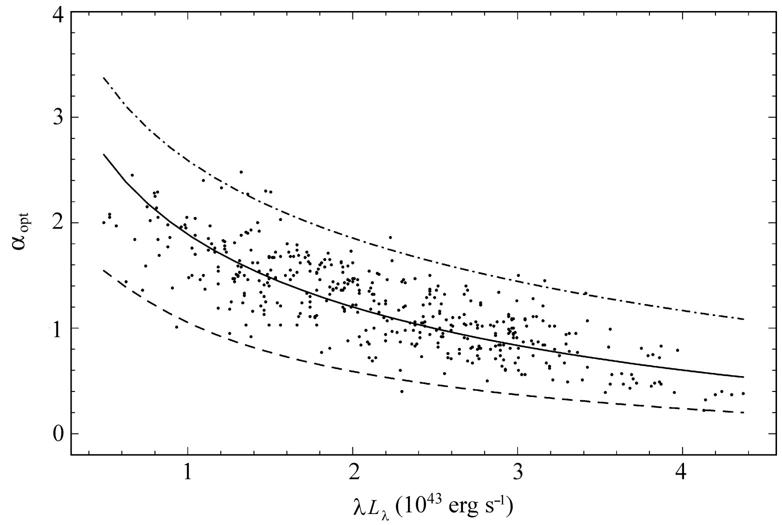

Fig. 4 Correlation of optical spectral index and the optical continuum luminosity at 5100 Å (rest frame) are modeled by a co-variable mode with $R_{\rm in}/R_{\rm s} = A\dot{m}^{-\beta}$. With luminosity increasing, the parameter is A $\sim$ 12.5 and $\beta \sim 0.4$ for dashed line, the dimensionless accretion rate $\dot{m}$ varying from 0.019 to 0.114 and the accretion radius from $60.7R_{\rm s}$ to $29.7R_{\rm s}$. For solid line, the parameters are A $\sim$ 12.5 and $\beta \sim 0.8$ with $\dot{m}$ varying from 0.05 to 0.16 and $R_{\rm in}$ from $133.9R_{\rm s}$ to $55.5R_{\rm s}$. For dot-dashed line, A $\sim 37.5R_{\rm s}$ and $\beta \sim 0.8$ with $\dot{m}$ varying from 0.11 to 0.26 and $R_{\rm in}$ from $218.1R_{\rm s}$ to $109.1R_{\rm s}$.

First, we tried to derive the theoretical relation between λL_λ (at 5100 Å) and $\alpha_{\rm opt}$ by varying the dimensionless accretion rate $\dot{m}$ ($\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ and $\dot{M}_{\rm Edd} = L_{\rm Edd}/\eta c^2$, where η is taken to be 0.1) at several certain inner radii of the accretion disk (Fig. 2). The different lines represent the model curves for $R_{\rm in} = 42R_{\rm s}, 82R_{\rm s}$ and $122R_{\rm s}$. It seems that the inner accretion disk radius $R_{\rm in}$ is close to a constant value $82R_{\rm s}$ from the best modeling, and the standard deviation $\sigma = 0.30$ with the dimensionless accretion rate $\dot{m}$ varies from 0.03 to 0.2. Here $\sigma = \sqrt{\sum_{i=1}^{N}(\alpha - \alpha_{\rm opt})^2/(N-1)}$, $\alpha_{\rm opt}$ is the observed optical spectral index and α is the model value.

Secondly, we tried to model the variations of λL_λ (at 5100 Å) and $\alpha_{\rm opt}$ at several certain accretion rate $\dot{m}$. As seen in Fig. 3, the different lines represent curves for $\dot{m} = 0.06$, 0.1 and 0.18. The best fitting was obtained from an accretion rate of $\dot{m} = 0.1$ with $\sigma = 0.38$ and the inner radius changing from $205.1R_{\rm s}$ to $19.6R_{\rm s}$.

It is also possible that the variations of the accretion rate can cause the variation of the inner boundary of a standard thin accretion disk if an ADAF-like accretion flow exists inside the standard disk (Narayan & Yi 1995). A possible co-varying mode could be in a form of $R_{\rm in}/R_{\rm s} = A\dot{m}^{-\beta}$. We tried this relation and derived the results shown in Fig. 4. The best fitting we found is for the value of A ∼12.5, and $\beta \sim 0.8$, i.e. $R_{\rm in} = 12.5\,R_{\rm s}\dot{m}^{-0.8}$, with $\sigma = 0.28$ when the accretion rate $\dot{m}$ changes from 0.05 to 0.16 and the inner disk radius changes simultaneously from about $55.5R_{\rm s}$ to $133.9R_{\rm s}$.

3.3 Analysis of the Results

From above modelings, one can see that the simple thin accretion disk model can explain the relation observed between the optical index and luminosity. The best fit is from a co-varying mode of $R_{\rm in} = 12.5\,R_{\rm s}\dot{m}^{-0.8}$. It indicates that the changes of the dimensionless accretion rate and the inner radius are probably related, and they work together for the variability of the continuum luminosity and optical index. If the optical continuum luminosity comes from the accretion disk itself, the variation of the dimensionless accretion rate of the accretion disk as well as the inner disk radius should be the key factors for the optical variation of NGC 5548.

Keeping a constant value of A ∼12.5 and $\beta \sim 0.8$ with the co-varying mode, one can obtain the dependence of the monochromatic luminosity at 5100 Å with $R_{\rm in}$, or with dimensionless accretion rate $\dot{m}$. When $R_{\rm in}$ becomes larger and dimensionless accretion rate $\dot{m}$ becomes less, the spectrum in the optical band tends to be softer (i.e. the optical spectral index increased), and the continuum luminosity gets fainter (Fig. 5). From Fig. 5, we can see that the variation timescale of $R_{\rm in}$ is roughly about several hundred days. The viscous timescale of a standard thin accretion disk can be expressed as $\tau_{\rm vis} \sim \frac{R^2}{\nu}$ (where ν is the viscosity parameter) or $\tau_{\rm vis} \sim \frac{R^2}{\alpha H^2 \Omega_k} \sim 10^3 \alpha^{-1} (\frac{M}{10^8\,{\rm M}_\odot})(\frac{H}{R})^{-1}(\frac{R}{R_{\rm s}})^{3/2}$. We note that if we set $\alpha = 0.1$ and $\frac{H}{R} = 0.1$, $\tau_{\rm vis}$ is about several hundred days for R being several tens of $R_{\rm s}$. This means that our result is consistent with the accretion disk model.

In Fig. 6, we show the variation of the transition velocity of inner disk radius; we used a ten-day average of $\Delta R/\Delta t$ of the neighboring data in order to avoid the large uncertainty caused by observation errors within short time interval. The transition velocity is in a range between several hundred and several thousand kilometers per second, with an average value of 1100 km s^{-1}. For R several tens Schwarzschild radii, this velocity suggests a time scale of variation of several hundred days, consistent with the viscous timescale given above for the radius.

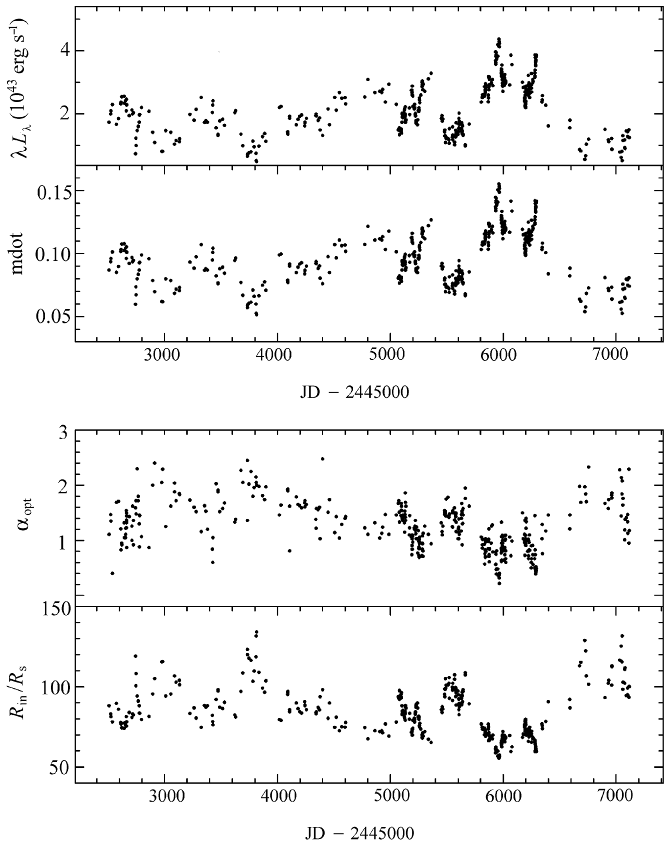

Fig. 5 With the thin accretion disk model of a co-variable mode of $R_{\rm in}/R_{\rm s} = 12.5\dot{m}^{-0.8}$, the monochromatic luminosity at 5100 Å seems to change very closely with dimensionless accretion rate $\dot{m}$, and the optical spectral index changes very closely with the inner accretion radius.

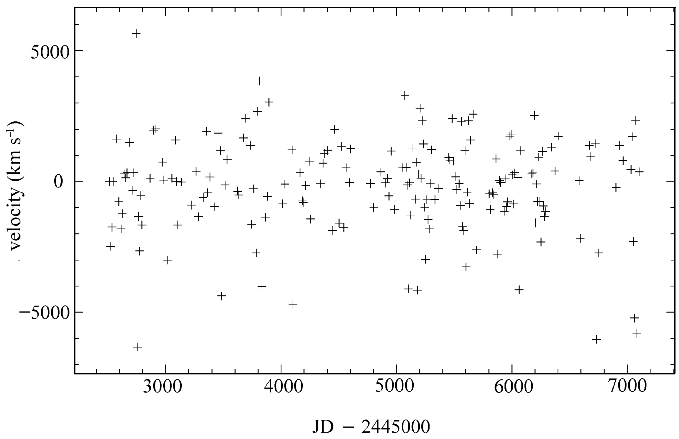

Fig. 6 Variable transition velocity of the inner disk radius with time, obtained from a ten-day average of $\Delta R/\Delta t$ in the neighboring calculated $R_{\rm in}$ in order to avoid the large uncertainty.

4 CONCLUSION AND DISCUSSION

In this paper, we adopt a simple standard thin disk model to explain the anti-correlation between the optical spectral index and the continuum flux at 5100 Å we obtained from optical spectra of NGC 5548. We conclude that changes of the dimensionless accretion rate and inner accretion disk in a co-variable mode of $R_{\rm in}/R_{\rm s} = 12.5\dot{m}^{-0.8}$ can explain well the optical flux and the spectral index variations. The inner accretion disk radius should vary with the accretion rate.

Interestingly, the dependence of the inner accretion disk radius on the accretion rate we obtained is in the form predicted by some theoretical works. Abramowicz et al. (1995) proposed that the transition varies between an inner ADAF and an outer disk can be expressed as $R_{\rm in}/R_{\rm s} \propto \dot{m}^{-2}$, while Liu et al. (1999) derived $R_{\rm in}/R_{\rm s} \propto \dot{m}^{-0.9}$ and Rozanska & Czerny (2000) gave $R_{\rm in}/R_{\rm s} \propto \dot{m}^{-1.3}$. Our result matches best the derivation of Liu et al. (1999) and supports an ADAF structure existing within an optically thick disk for NGC 5548. The size of the ADAF disk is about $133R_{\rm s}$ in the low luminosity state and $60R_{\rm s}$ in the high luminosity state.

We have assumed the optical continuum radiation comes mainly from an optically thick, geometrically thin accretion disk and adopted the temperature distribution in a standard steady disk model for simplicity. We noticed that both the accretion rate and inner disk radius are variable in NGC 5548, so the accretion disk structure of this source can not be a steady one. However, we may expect that even in a non-steady disk the temperature profile may not be too different from that in a steady disk because it is mainly related to the viscous dissipation process. The accurate temperature profile can only be estimated if we do a time-dependent study of the disk structure involving an inner ADAF and an outer thin disk.

There could be some other physical process causing variability of the optical luminosity. The reprocessing model suggests that the optical flux could be produced by seed photons coming from a hot Comptonizing region in the central region and reprocessed by the cold disk outside. However, this can only explain the correlation of the flux in the optical and X-ray bands. That the amplitude of the X-ray variability is less than that of the optical variability (Uttley et al. 2003) indicates that the disk thermal reprocessing is not the main, or at least not the only, mechanism for the optical variations. The changes of the inner disk radius due to the thermal instabilities (Treves et al. 1988) can certainly cause the optical variation. The reprocessing mechanism presented by Chiang (2002) and Chiang & Blaes (2003) should lead to a decrease in the high accretion rate from the simple thin accretion disk model we obtained in this paper, and could hopefully explain the correlation both in the X-ray band and optical continuum as well as the larger amplitude of the optical continuum variations as compared to the X-ray.

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References

Abramowicz M. A., Chen X., Kato S. et al., 1995, ApJ, 438, L37
Beloborodov A. M., 1999, ApJ, 510, L123
Boroson T. A., Green R. F., 1992, ApJS, 80, 109
Chiang J., Blaes O., 2001, ApJ, 557, L15
Chiang J., 2002, ApJ, 572, 79
Chiang J., Blaes O. M., 2003, ApJ, 586, 97
Clavel J., Reichert G. A., Alloin D. et al., 1991, ApJ, 366, 64
Clavel J., Nandra K., Makino F. et al., 1992, ApJ, 393, 113
Dietrich M., Kollatschny W., Peterson B. M. et al., 1993, ApJ, 408, 416
Frank J., King A., Raine D., 1992, Sci, 258, 1015
Howarth I. D., 1983, MNRAS, 203, 301
Kaspi S., Smith P. S., Netzer H. et al., 2000, ApJ, 533, 631
Kawaguchi T., Mineshige S., Umemura M. et al., 1998, ApJ, 504, 671
Korista K. T., Alloin D., Barr P. et al., 1995, ApJS, 97, 285
Liu B. F., Yuan W., Meyer F. et al., 1999, ApJ, 527, L17
Magdziarz P., Blaes O. M., Zdziarski A. A. et al., 1998, MNRAS, 301, 179
Narayan R., Yi I., 1995, ApJ, 452, 710
Peterson B. M., Balonek T. J., Barker E. S. et al., 1991, ApJ, 368, 119
Peterson B. M., Alloin D., Axon D. et al., 1992, ApJ, 392, 470
Peterson B. M., Berlind P., Bertram R. et al., 1994, ApJ, 425, 622
Peterson B. M., Barth A. J., Berlind P. et al., 1999, ApJ, 510, 659
Peterson B. M., Berlind P., Bertram R. et al., 2002, ApJ, 581, 197
Romanishin W., Balonek T. J., Ciardullo R. et al., 1995, ApJ, 455, 516
Rozanska A., Czerny B., 2000, A&A, 360, 1170
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Treves A., Maraschi L., Abramowicz M., 1988, PASP, 100, 427
Trevese D., Vagnetti F., 2002, ApJ, 564, 624
Trevese D., Vagnetti F., 2001, MmSAI., 72, 33
Uttley P., Edelson R., McHardy I. M. et al., 2003, ApJ, 584, L53
Uttley P., McHardy I. M., Papadakis I. E., 2002, MNRAS, 332, 231
Van G. E., Wanders I., 1992, PASP, 104, 700
Wanders I., Peterson B. M., 1996, ApJ, 466, 174
Wandel A., Peterson B. M., Malkan M. A., 1999, AJ, 526, 579
Wilson A. S., Ulvestad J. S., 1982, ApJ, 260, 56
Wrobel J. M., 2000, ApJ, 531, 716
Wu X. B., Han J. L., 2002, ApJ, 561, L59
Zdziarski A. A., Lubinski P., Smith D. A., 1999, MNRAS, 303, L11
Zhang T. Z., Wu X. B., 2002, Chin. J. Astron. Astrophys., 2, 487