A test of the failed disc wind scenario for the origin of the broad-line region in active galactic nuclei

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ABSTRACT
It has been recently proposed that the broad-line region in active galactic nuclei originates from dusty clouds driven from the accretion disc by radiation pressure, at a distance from the black hole where the disc is cooler than the dust sublimation temperature. We test this scenario by checking the consistency of independent broad-line region and accretion disc reverberation measurements, for a sample of 11 well-studied active galactic nuclei. We show that independent disc and broad-line region reverberation mapping measurements are compatible with a universal disc temperature at the Hβ radius of $T(R_{H\beta}) \approx 1670 \pm 231$ K which is close to typical dust sublimation temperatures.

Key words: galaxies: active – quasars: general – galaxies: Seyfert.

1 INTRODUCTION
Broad emission lines in the optical and UV bands are prominent features in many active galactic nucleus (AGN) spectra. The Unified Model of AGNs (Antonucci & Miller 1985) assumes that broad emission lines seen in AGNs are generated in a zone called the broad-line region (BLR) located between a thick dusty torus and the central black hole (BH), in a region close to the accretion disc plane (Suganuma et al. 2006; Gaskell 2009). Even though there are still some open problems regarding the physics and the geometry of the BLR (see Gaskell 2009 for a review) recent results seem to converge towards a scenario where the BLR is made of optically thick dusty clouds rotating around the BH in a roughly Keplerian fashion with the addition of some local turbulence (Done & Krolik 1996; Bottorff et al. 1997; Marconi et al. 2008; Denney et al. 2009). Emission line reverberation mapping studies (Kaspi et al. 2000; Peterson et al. 2004; Bentz et al. 2009) show a tight relation between the Hβ effective BLR radius and the monochromatic continuum luminosity at 5100 A:

$$R_{H\beta} \propto \sqrt{L_{5100}}.$$  

(1)

Although the $R_{BLR}-L$ relation is well established and even used in an attempt to constrain cosmology (Watson et al. 2011), there is still an ongoing debate regarding its origin. Some of the proposed models for the BLR formation (Elvis 2000; Elitzur 2008) imply some kind of outflow from the disc that is either driven by radiation pressure (Chiang & Murray 1996) or by the local magnetic field (Blandford & Payne 1982).

Recently, Czerny & Hryniewicz (2011, hereafter CH) proposed a simple formation mechanism for the BLR that naturally accounts for most of the observed properties of the BLR (e.g. the $R_{BLR}-L$ relation, the observed turbulence in cloud motions and the universality of the $R_{BLR}-L$ relation among narrow-line and non-narrow-line Seyferts 1). This ‘failed disc wind’ scenario predicts that the BLR is made by dusty clouds driven above the accretion disc plane by radiation pressure, at radii where the underlying accretion disc is cooler than the dust sublimation temperature ($T_{sub} \sim 1000$ K). When the clouds rise at a sufficient height above the disc plane, the intense ionizing radiation makes the dust sublimate. As a consequence, the clouds lose radiation pressure support and fall back on the disc plane. The mix of rising and falling clouds generates a kind of boiling motion. This hypothesis effectively imposes a minimum radius to the inner edge of the BLR that is determined by the radius where the accretion disc has $T_{el} \approx T_{sub}$. In this paper, we check the consistency between independent optical continuum (disc) and Hβ (BLR) reverberation mapping measurements for a sample of 11 AGNs. In Section 2, we describe the AGN sample and the data set. In Section 3, we discuss our method. In Section 4, we show our results. Finally, we draw our conclusions in Section 5.

2 THE AGN SAMPLE
Our sample consists of 11 bright AGN for which there are both disc (Cackett, Horne & Winkelr 2007) and Hβ (Bentz et al. 2009) reverberation mapping measurements (see Table 1). Our sample consists mostly of type 1 Seyfert galaxies, and spans a range of redshift between $z \sim 0.002$ and $z \sim 0.06$. For the disc reverberation, we use results from Cackett et al. (2007) where the authors measured time delays for a sample of 14 AGN observed in optical $BVRI$ bands by Sergeev et al. (2005). The authors fit a reddened thin accretion disc model (Shakura & Sunyaev 1973) to the variable component of their light and obtain optical continuum time delays by cross-correlation analysis of the light curves. For the Hβ reverberation, we use

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results from Bentz et al. (2009) where host galaxy contamination was carefully taken into account using high-resolution Hubble Space Telescope images.

3 METHOD

We assume a simple thin steady-state accretion disc model (Shakura & Sunyaev 1973)

\[ R = \left(\frac{3GM\dot{M}}{8\pi\sigma T^3}\right)^{1/3}, \]  

(2)

where \( T \) and \( R \) are the temperature and radius, respectively, \( M \) the BH mass, \( \dot{M} \) the accretion rate and \( \sigma \) the Stefan-Boltzmann constant.

The scenario proposed by CH predicts a disc temperature at the H\( \beta \) radius that is universal among AGN and close to typical dust sublimation temperatures (1000 K < \( T_{\text{sub}} \) < 2000 K):

\[ T_{\text{eff}}(R_{\text{H}\beta}) \approx T_{\text{sub}}. \]  

(3)

Parametrized in terms of the H\( \beta \) time lag \( \tau = R_{\text{H}\beta}/c \) and the \( \dot{M}M \) product, equations (2) and (3) translate to the following relation

\[ \log(\tau) \approx 3.001 - \frac{4}{3} \log(T) + \frac{1}{3} \log(\dot{M}M), \]  

(4)

where \( \tau \) is in days and \( \dot{M}M \) in \( M_\odot \) yr\(^{-1}\). We use the above relation to test the predictions of the failed disc wind scenario and the consistency of disc/BLR reverberation measurements.

4 DATA ANALYSIS AND RESULTS

Our first fit considers a power-law model for the time delay \( \tau \) as a function of \( \dot{M}M \). Fig. 1 shows the data points and error bars from Table 1 transformed on to logarithmic scales. When asymmetric error bars are given for \( \tau \), we use their geometric mean. A correlation is evident in Fig. 1, and the slope can be judged by eye to be close to the theoretical slope of 1/3, as indicated by the dashed curves for three disc temperatures. In Fig. 1, we fit a two-parameter linear relationship between \( \log(\tau) \) and \( \log(\dot{M}M) \), accounting for the error bars on both axes. As shown in Fig. 1, we find a best-fitting slope of \( \alpha = 0.408 \pm 0.045 \). As this is only 1.6\% steeper than the theoretical slope 1/3, we conclude that the data are consistent with the theory. The reduced \( \chi^2 \) (3.81 with 9 degrees of freedom) indicates a larger scatter among the data points than can be accounted for by the observational errors. Thus, if the error bars are reliable, our fit provides some evidence that the disc temperature at the H\( \beta \) radius varies from object to object. To quantify the object-to-object distribution of disc temperatures at the H\( \beta \) radius, we define a two-parameter model with centroid temperature \( T_0 \equiv \exp(\langle \ln T \rangle) \) and a temperature dispersion \( \Delta T \equiv T_0 \sigma(\ln T) \). Our maximum likelihood fit, shown in Fig. 2, gives \( T_0 = 1670 \pm 231 \) K and \( \Delta T = 573 \pm 172 \). The reduced \( \chi^2 / \nu \) is now 1, compatible with the scatter by virtue of the intrinsic dispersion. The parameters are well enough defined that the posterior distribution is Gaussian (lower panel of Fig. 2). Our results indicate that the accretion disc temperature at the H\( \beta \) radius is 1670 ± 231 K which is quite close to typical dust sublimation temperatures. This value is ≈ 700 K higher than that obtained by CH (994 ± 74 K). This difference can be largely accounted for by

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Table 1. AGN data from disc and H\( \beta \) reverberation mapping.

| Name      | Type | \( z \) | \( \log[\dot{M}M]\) [\( M_\odot \) yr\(^{-1}\)] \( ^a \) | \( \tau(\text{H}\beta) \) (d) \( ^b \) | \( T(R_{\text{H}\beta}) \) (K) |
|-----------|------|--------|-------------------------------|-------------------------------|---------------|
| NGC 4051  | Sy 1 | 0.00243| 5.06 ± 1.14                 | 5.8 ± 2.6                   | 1183 ± 846   |
| NGC 4151  | Sy 1.5| 0.00332| 5.92 ± 0.16                 | 6.6 ± 1.1                   | 1326 ± 187   |
| NGC 3227  | Sy 2 | 0.00386| 5.97 ± 0.40                 | 7.8 ± 3.5                   | 2735 ± 1691  |
| NGC 3516  | Sy 1.5| 0.00884| 6.96 ± 0.56                 | 6.7 ± 3.8                   | 3281 ± 2142  |
| NGC 7469  | Sy 1 | 0.01632| 6.89 ± 0.36                 | 4.5 ± 0.7                   | 3169 ± 769   |
| NGC 5548  | Sy 1.5| 0.01718| 8.54 ± 0.23                 | 18 ± 0.6                    | 2817 ± 384   |
| Mrk 79    | Sy 1 | 0.02219| 7.49 ± 0.31                 | 15.2 ± 3.4                  | 1868 ± 508   |
| Mrk 335   | Sy 1 | 0.02579| 7.60 ± 0.31                 | 15.7 ± 3.4                  | 1904 ± 479   |
| Ark 120   | Sy 1 | 0.03271| 7.86 ± 0.34                 | 39.7 ± 3.9                  | 1074 ± 231   |
| Mrk 509   | Sy 1.5| 0.0344 | 8.65 ± 0.31                 | 79.6 ± 5.4                  | 998 ± 185    |
| 3C 390.3  | Sy 1.5| 0.0561 | 7.65 ± 0.67                 | 23.6 ± 6.7                  | 1543 ± 678   |

\( ^a \) From Cackett et al. (2007).  
\( ^b \) From Bentz et al. (2009).
Figure 2. Upper panel: two-parameter maximum likelihood fit to the data in Table 1. Here the two free parameters are a centroid temperature $T_0$ and a temperature dispersion $\Delta T$. The continuous lines represent the best-fitting model and the span due to the intrinsic scatter. The dashed lines show equation (4) plotted for three different temperatures. Lower panel: posterior probability distribution of the parameters. The contours represent 1, 2 and 3σ confidence regions.

the differences in the assumed Hβ reprocessing geometry between our and CH work. The time delay at radius $R$ is

$$\tau = (R/c)(1 + \sin i \cos \theta),$$  

where $i$ is the inclination to the line of sight and $\theta$ the azimuthal angle. CH assumes a mean BLR inclination of $i = 39.2^\circ$ and that the Hβ emission arises primarily from the part of the BLR farthest away from the observer such that $\cos \theta \approx 1$. With these assumptions the time delay increases by a factor $\tau = 1.63 (R/c)$. We assume instead that the Hβ response is roughly uniformly distributed in azimuth such that $\langle \cos \theta \rangle = 0$. Considering the $T \propto R^{-3/4}$ relation, one finds that our temperature is $(1 + \sin i)^{0.75} = 1.44$ times higher than in the case of emission coming from the farthest side of the BLR. Correcting by this factor yield a temperature centroid of $T(R_{\text{H} \beta}) \approx 1160$ K which is much closer to CH value.

The intrinsic temperature scatter of $\Delta T = 573 \pm 172$ is not surprising, considering that Hβ delays and $\dot{M}$ measurements are not simultaneous and thus do not correspond to the same disc luminosity.

5 CONCLUSIONS

We have shown that independent disc and Hβ reverberation mapping measurements are compatible with a universal disc temperature at the Hβ radius of $T(R_{\text{H} \beta}) \approx 1670 \pm 231$ K which is close to typical dust sublimation temperatures. Our results are therefore compatible with the failed disc wind scenario for the origin of the BLR proposed by CH. In this framework, the $R_{\text{BLR}}-L$ scaling relation can be interpreted as a consequence of the accretion disc luminosity–radius scaling explored in Cackett et al. (2007) and the existence of a universal dust sublimation temperature among AGN.

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