The location of the dust causing internal reddening of active galactic nuclei

Clio Z. P. Heard and C. Martin Gaskell

Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064

ABSTRACT

We use the Balmer decrements of the broad-line regions (BLRs) and narrow-line regions (NLRs) of active galactic nuclei (AGNs) as reddening indicators to investigate the location of the dust for four samples of AGNs with reliable estimates of the NLR contribution to the Balmer lines. Intercomparison of the NLR and BLR Balmer decrements indicates that the reddening of the NLR sets a lower limit to the reddening of the BLR. Almost no objects have high NLR reddening but low BLR reddening. The reddening of the BLR is often substantially greater than the reddening of the NLR. The BLR reddening is correlated with the equivalent widths of [O\textsc{iii}] lines and the intensity of the [O\textsc{iii}] lines relative to broad H\beta. We find these relationships to be consistent with the predictions of a simple model where the additional dust reddening the BLR is interior to the NLR. We thus conclude that the dust causing the additional reddening of the accretion disc and BLR is mostly located at a smaller radius than the NLR.

Key words:
galaxies: active – galaxies: nuclei – galaxies: Seyfert – dust, extinction

1 INTRODUCTION

The standard model for active galactic nuclei (AGNs) assumes that the central supermassive black hole is surrounded by an accretion disc (AD) and broad-line region (BLR). These in turn are surrounded by a dusty torus, and a narrow-line region (NLR) is further out. Early optical spectroscopy of active galactic nuclei (AGNs) indicated that there were two broad categories: Seyfert 1s, where broad Balmer lines are prominent in spectra, and Seyfert 2s, where broad Balmer lines are lacking (Khachikian & Weedman 1971). The discovery by Keel (1980) that Seyfert 1s are preferentially seen face-on led to the unified model for thermal AGNs: that they are all the same type of object, only seen from different viewing angles or at different levels of activity (see Antonucci 1993, 2012).

Even though it has been recognized since Keel (1984) that obscuring off-axis dust is an essential component of AGN models, there has been long-standing controversy over the distribution of this dust. The optically-thick dust in a plane perpendicular to the axis of symmetry of an AGN is commonly considered to be a torus (see Antonucci 1993) but an alternative possibility is that the obscuring dust needed for the unified model is the outer regions of a wind where dust uplifted from the surface of the outer accretion disc is embedded in an outflow (Konigl & Kartje 1994). Closely related to the question of the distribution of dust is the question of how much extinction there is in AGNs (see Gaskell 2015 for a review of the history). The extinction of the various components of an AGN gives us valuable information about the location of the dust.

Since the earliest spectrometry AGNs there has been no doubt that the NLR is reddened (Wampler 1968, Gaskell 1982, 1984) and Wysota & Gaskell (1988) show that there is agreement between a variety of reddening indicators for permitted and forbidden lines. The median reddening of the NLRs considered by Gaskell (1984) and Wysota & Gaskell is $E(B-V) \approx 0.30$ with a standard deviation of $\pm 0.35$. From the narrow-line Balmer decrement alone, Koski (1978) found a median reddening for Seyfert 2’s of 0.52 with a standard deviation of 0.25.

From the Hubble Space Telescope imaging survey of Schmitt et al. (2003), the median radius enclosing half the power of the [O\textsc{iii}] emission is 520 parsecs. However, temporal variability shows that there is substantial [O\textsc{iii}] emission much closer to the center. For example, Zheng et al. (1993) find the size of the NLR of 3C 390.3 to be $\sim 1$ light-year and Peterson et al. (2013) find the size of the NLR of NGC 5548...
to be 3–10 light-years. In contrast to this, the broad-line region (BLR), has a much smaller size (light-days to light-weeks for a typical Seyfert galaxy), and is located close to the accretion disc (see Gaskell 2009).

In addition to off-axis dust in the torus, which does not obscure our line of sight for type-1 viewing angles, dust can be located in the following three locations:

(A) Between the observer and all components of the AGN. This includes dust in the Milky Way and far from the AGN in the host galaxy.

(B) Intermingled with the NLR gas.

(C) Between the NLR and the BLR. This dust might be from the torus or in a dusty outflow.

Our view of the various components of an AGN can be reddened by combinations of dust in different locations. Figure 1 shows the possible configurations of dust in these three locations, and Figure 2 illustrates some of the ways each configuration could occur for a real AGN.

An important question is, might the same dust that causes reddening in the NLR also cause reddening in the BLR and continuum? If the NLR and the BLR are just both reddened by the same foreground dust (see case IV in Figure 2), the reddening should be similar and the reddenings should be correlated. If the dust is predominantly closer to the center than the NLR (e.g., cases III or VII in Figure 2), the BLR reddening will be greater and not correlated with the NLR reddening. Thus, by comparing the reddening of the NLR and the BLR, we can get a better idea of where the dust is located. In this paper, we compare the reddenings of the NLR and the BLR along with other properties in order to distinguish between possible locations of the dust.

Reddenings can be estimated from observations of line ratios if the theoretical ratio is known. Line ratios include hydrogen and helium recombination lines and, for low-density gas, some forbidden-line ratios. Permited lines of H\textsc{i} and He\textsc{ii} are produced by both high- and low-density gas. However, the line ratios can potentially be modified by optical depth and collisional effects (see Gaskell 2015 for details). If these effects are significant, they would be greatest for hydrogen. Permited He\textsc{ii} lines are affected less because the energy levels are four times higher, the abundance of helium is one tenth of hydrogen, and the size of the He\textsc{++} zone is relatively small. He\textsc{ii} line ratios are considered to be a good reddening indicator including for the high-density gas of the BLR (Shuder and MacAlpine 1979, MacAlpine 1981).

Although radiative-transfer and collisional effects have widely been considered to be more important for the BLR, a study of blue AGNs (defined as having a continuum slope \(\alpha_\lambda \geq 1.5\), where \(\alpha_\lambda\) is fitted in the rest-wavelength range of 4030 – 5600 Å, which are assumed to have low reddening, by Dong et al. (2008) implies that the H\textsc{a}/H\textsc{beta} is close to the theoretical Case B ratio and can be used as a reddening indicator. Investigation of the Balmer decrement of even bluer AGNs implies a mean unreddened, velocity-integrated H\textsc{a}/H\textsc{beta} ratio of 2.72 ± 0.04 (Gaskell 2013), i.e., within the range of Case B values (see Storey & Hummer 1995).

For the low-density NLR, calculations have long indicated that the hydrogen-line ratios can be used as a reddening indicator (e.g., Gaskell & Ferland 1984). This is supported by comparisons between reddenings estimated from NLR Balmer decrements and estimates from other line ratios such as He\textsc{ii} and forbidden lines (see above). However, because the hydrogen lines are strong, and thus can be measured in a large number of objects, we will only consider reddenings given by the BLR and NLR Balmer decrements in this study.

Dust along the line of sight not only makes things redder, but also makes them fainter. If the dust is predominantly located between the BLR and the NLR, it will make both the accretion disc and the BLR look fainter relative to the NLR. We will therefore also compare the BLR H\textsc{a}/H\textsc{beta} ratio to the [O\textsc{iii}] equivalent width and to the ratio of [O\textsc{iii}] to H\beta_{BLR}.

2 SAMPLE SELECTION

In order to analyze the reddening of the NLR and BLR, we chose samples with high-quality spectra. Although a very large number of AGN spectra are available from the SDSS, the quality of many spectra is too low to allow a reliable separation of broad- and narrow-line components, and thus they cannot provide reliable estimates of NLR contribution. Samples from Lick observatory (Cohen 1983 and Osterbrock 1977) had very high signal-to-noise ratios and careful separation of broad- and narrow-line components. Dong et al. (2005) present a sample of AGNs with very steep Balmer decrements for which they have carefully subtracted the stellar continuum and separated broad- and narrow-line components. We have also included the very blue AGN sample of Dong et al. (2008) which will have very low reddening of the continuum.

3 BROAD-LINE VERSUS NARROW-LINE REDDENING

A straightforward question is whether the reddenings of the BLR and NLR are correlated. If both are reddened by a common screen of dust along the line of sight (case IV in Figures 1 and 2), we would expect their reddenings to be correlated. In Figure 3 we show the broad- and narrow-line
Balmer decrements for the 300 highest quality AGN spectra of the sample of Dong et al. (2005) (see their Figure 8). The solid square indicates the expected unreddened line ratios. For the BLR, Gaskell (2015) finds $H\alpha/H\beta = 2.74$. For the NLR, simple recombination theory predicts $H\alpha/H\beta \approx 2.9$ (see Osterbrock & Ferland 2006) and comparison with other line ratios suggests $H\alpha/H\beta \approx 3.1$ (Gaskell 1982, 1984; Wysota & Gaskell 1988). The arrow indicates the expected trend if the NLR and BLR have common reddening.

Four things can be noticed from Figure 3:

(i) The most noticeable thing is, at any given NLR Balmer decrement, the flattest BLR decrements (lowest-ratio) are similar to the narrow-line decrement; i.e., the lower envelope is a 45-degree line parallel to the reddening vector. The null hypothesis, that the minimum BLR decrement is independent of the NLR decrement (see, for example, Figure 2, panel VI), is excluded at a probability $p = 0.002$.

(ii) There is a lack of AGNs with NLR decrements steeper than the BLR decrement. Points to the right of the 45 degree line are consistent with measuring errors. Only one point lies more than two standard deviations to the lower right of the red line.

(iii) For the majority of AGNs the BLR decrement is steeper than the NLR decrement.

(iv) There is no significant difference in the median NLR decrement for the AGNs with very steep BLR Balmer decrements compared with those with very flat BLR Balmer decrements.

These results are consistent with the earlier findings of De Zotti & Gaskell (1985) and Glikman et al. (2007). De Zotti & Gaskell (1985) found that Balmer decrements for nearby AGNs were steeper for the broad lines than the narrow lines, and Glikman et al. (2007) found that, for the FIRST-2MASS red quasar survey, broad lines seem to be reddened more than the sum of broad and narrow lines.

Our results strongly imply that:

(i) The dust that reddens the NLR also reddens the BLR, but

(ii) most of the dust reddening the BLR lies between the BLR and the NLR.

The dust causing the common reddening of both the NLR and BLR could be associated with the NLR or it could be dust in the host galaxy. De Zotti & Gaskell (1985) studied nuclear continuum colors and both broad- and narrow-line Balmer decrements of nearby AGNs as a function of the orientation of the host galaxy. They found that for more highly inclined disc galaxies the nuclear colors were redder and the Balmer decrements steeper. Since the axis of symmetry of an AGN is not necessarily aligned with the rotation axis of the galaxy (see, for example, Tohline & Osterbrock 1982; Valtonen 1983; Battye & Brown 2009), the greater

\[ A \] a slightly greater intrinsic $H\alpha/H\beta$ ratio for the NLR is expected on theoretical grounds because (a) at a given temperature the Case B ratio for pure hydrogen is lower at high densities (see Figure 4 of Gaskell 2015), and (b) the temperature is somewhat lower in the NLR than the BLR for the same ionization conditions because there is additional forbidden-line cooling at NLR densities. Lower temperatures cause steeper Balmer decrements (see Osterbrock & Ferland 2006).
nuclear reddening of inclined galaxies must be due in part simply to dust in the plane of the galaxy.

4 THE RELATIVE STRENGTH OF [O III] VERSUS THE BLR REDDENING

As noted above, intervening dust not only causes reddening, but also extinction. If the dust is located between the NLR and the BLR, we would expect higher extinction of the BLR and accretion disc to make [O III] stronger relative to the BLR and the continuum.

4.1 Selection of Objects

[O III] λ5007 is the strongest narrow line in the optical and the Balmer lines are the strongest broad lines. Therefore, a very large number of measurements are potentially available in the Sloan Digital Sky Survey (SDSS). Dong et al. (2008) have carefully measured Hα/Hβ ratios after subtraction of narrow lines and Fe II, etc. Comparison of their ratios with the simple gaussian fits of the SDSS pipeline reveals quite a few very discrepant measurements in the SDSS database and that the difference between the Dong et al. (2008) measurements and the SDSS is around ±0.2 dex (i.e., a factor of 50%).

The Lick Observatory data of Osterbrock (1977) and Cohen (1983) are of much higher signal-to-noise ratio than most SDSS spectra. This allowed them to carry out careful deblending of lines. We have therefore used the Lick data and the line intensity measurements of Dong et al. (2005, 2008) from SDSS spectra. The latter do not give [O III] intensities and Hβ equivalent widths, so we have taken these values from the SDSS.

4.2 [O III]/Hβ

Figure 4 shows the [O III]/HβBLR ratio versus the broad line Hα/Hβ ratio. The red lines indicate the expected change in the ratios for reddening of the BLR alone. The separation between the two lines indicates the probable intrinsic scatter in the [O III]/HβBLR ratio. It can be seen that there is a positive correlation between the [O III]/HβBLR ratio and the BLR Balmer decrement, suggesting that dust lying between the two emitting regions causes extinction of the continuum.

We note that the SDSS observations show more scatter than the higher quality Lick observatory observations. The Hβ flux appears in the denominator of both axes in Figure 4, so an error in Hβ could cause a spurious correlation. However, this correlation, indicated by the green arrow in Figure 4, is mostly not in the same direction as the observed correlation and the effect is expected to be small.

The length of the arrow corresponds to a 20% error in the Hβ flux (more than double the typical error of Dong et al. (2005)). Nonetheless, it is possible that large measuring errors for very weak Hβ lines enhanced the correlation in the upper right of the diagram. To test for this, in Figure 5 we show the [O III]/HβBLR ratio versus Hα/Hβ. In this case large measuring errors would cause a decrease in log[O III]/HβBLR as indicated by the green arrow. The similarity between Figures 4 and 5 argues against the trend in Figure 4 being due to measuring errors in the Hβ flux.

The observations of Dong et al. (2005) of AGNs with very steep Balmer Decrements (indicated by diamond symbols in Figures 4 and 5) seem to have systematically lower [O III]/HβBLR values. We suspect that the lower signal noise of the SDSS spectra could be contributing to this as well. Visual inspection of the spectra suggests that the discrepancy is due to underestimation of the flux in the [O III] line broad wings, which contain a substantial amount of the [O III] flux. There is probably also a selection bias against finding AGNs...
with extremely high \([\text{O}_{\text{III}}]/H_\beta\) ratios because broad H\(\beta\) is so weak. Objects with very high \([\text{O}_{\text{III}}]/H_\beta\) would be classified as Seyfert 2s.

The correlations in Figures 4 and 5 and the qualitative agreement with a simple BLR reddening model are consistent with reddening of AGNs mostly being caused by dust between the NLR and BLR.

### 4.3 Apparent Equivalent Width of \([\text{O}_{\text{III}}]\)

As an additional check we also looked at the ratio of \([\text{O}_{\text{III}}]\) to the continuum, i.e., the equivalent width (EW) of \([\text{O}_{\text{III}}]\). The observed continuum includes light from the AGN and starlight in the host galaxy. Figure 6 shows the EW of \([\text{O}_{\text{III}}]\) against the broad line H\(\alpha\)/H\(\beta\) ratio. Cohen (1983) did not give EWs of \([\text{O}_{\text{III}}]\), so those results (the squares in Figures 4 and 5) are not included. For the flatter BLR Balmer decrements, there is the expected increase in apparent equivalent width of \([\text{O}_{\text{III}}]\). However, for steeper decrements, the apparent equivalent width appears to plateau. Again, there is more scatter for the SDSS measurements and, for reasons that have been discussed above, the \([\text{O}_{\text{III}}]\) equivalent widths are systematically lower.

As shown by the curves in Figure 6, the plateauing in the apparent equivalent width of \([\text{O}_{\text{III}}]\) is just what is expected from the simple BLR reddening model. This is because observed EWs measure the intensity of an emission line relative both to the light of the accretion disc and the starlight of the host galaxy. We assume that the reddening only affects the light of the inner regions of the AGN and not the starlight. This naturally produces the saturation in \([\text{O}_{\text{III}}]\) equivalent width. To give the approximate envelopes of the distribution in Figure 6, the unreddened EW varies by \(\pm 0.4\) dex and the average fraction of host galaxy starlight for the least-reddened AGNs is \(\approx 0.2\) at \(\lambda 5000\).

It is interesting to compare the contributions of host galaxy starlight needed to explain the variation of \([\text{O}_{\text{III}}]\) equivalent width with independent estimates of host galaxy fractions. The reddening of most BLRs and accretion discs is not zero but it is easy to predict the fractions of host galaxy starlight as a function of H\(\alpha\)/H\(\beta\) from our model. The AGNs in the Osterbrock sample include many well-studied bright AGNs. The median H\(\alpha\)/H\(\beta\) \(\approx 4\). For this value, our model described in the previous paragraph predicts a galaxy starlight fraction of 0.4. Hubble Space Telescope imaging by Bentz et al. (2013) of reverberation-mapped AGNs (a sample with large overlap with Osterbrock 1977 and observed with similar ground-based apertures) shows a mean fraction of 0.42.

Vanden Berk et al. (2006) have estimated the fractional contributions of the host galaxy starlight at \(\lambda 4200\) for most of the SDSS AGNs considered here. The median host galaxy starlight fraction at \(\lambda 4200\) for the Dong et al. (2008) objects is 0.08 while the median host galaxy fraction for the Dong et al. (2003) objects is 0.6.

The consistency between the variation of the equivalent width of \([\text{O}_{\text{III}}]\) with reddening and the simple predictions (Figure 6) further reinforces the picture that the dust causing reddening in AGNs lies mainly between the NLR and the BLR.

### 5 CONCLUSIONS

Using observed BLR Balmer decrements as reddening indicators, we conclude from the sample of AGNs we have studied that

(i) The BLR is almost always reddened at least as much
Figure 6. The logarithms of the equivalent widths of [O iii] λ5007 (in Å) plotted against the broad line Hα/Hβ ratio. Triangles are measurements from Osterbrock (1977), diamonds are measurements from Dong et al. (2005) and the SDSS, and small dots are from Dong et al. (2008) and the SDSS. The curves show the changes in apparent equivalent width (relative to both the accretion disc and the host galaxy) predicted by our simple model as discussed in the text. The lower curve corresponds to an unreddened apparent equivalent width ratio 3 Å and the upper curve to 45 Å. The fraction of host galaxy light at λ5000 has been taken to be 0.2. The vertical dashed lines indicate ∆E(B − V) of 0.1.

as the NLR, suggesting there is common intervening reddening in most cases.

(ii) As the reddening of the BLR increases, the relative intensity of the [O iii] lines increases compared to both broad Hβ and to the continuum.

(iii) This increase in [O iii]/HβBLR and apparent EW([O iii]) with increasing BLR reddening is naturally explained by additional reddening of the BLR and continuum alone.

If these results apply to all AGNs, they imply two important things. Firstly, they provide support for steep BLR decrements being a consequence of reddening rather than intrinsic steepening due to radiative transfer and collisional effects in the BLR clouds. Secondly, they imply that the dust causing reddening of the continuum and BLR is mostly located between the NLR and the BLR. The most natural origin of this dust is to be blown off of the torus, or indeed even to be what is regarded as the torus. The common reddening of the NLR and BLR could be due to dust associated with the NLR or other dust in the host galaxy.

ACKNOWLEDGMENTS

We are grateful for the feedback and advice from Xiaobo Dong and Ski Antonucci. We thank the anonymous referee for detailed and helpful comments which have improved the paper.

REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473
Antonucci, R. 2012, Astron and Astrophys Trans, 27, 557
Battye, R. A., & Browne, I. W. A. 2009, MNRAS, 399, 1888
Bentz, M. C., Denney, K. D., Grier, C. J., et al. 2013, ApJ, 767, 149
Cohen, R. D. 1983, ApJ, 273, 489
De Zotti, G. & Gaskell, C. M. 1985, A&A, 147, 1
Dong, X.-B., Zhou, H.-Y., Wang, T.-G., et al. 2005, ApJ, 620, 629
Dong, X., Wang, T., Wang, J., et al. 2008, MNRAS, 383, 581
Gaskell, C. M. 1982, PASP, 94, 891
Gaskell, C. M. 1984, Astrophysical Letters, 24, 43
Gaskell, C. M. 1988, ApJ, 325, 114
Gaskell, C. M. 2009, New Astron. Rev, 53, 140
Gaskell, C.M. 2015, MNRAS submitted (arXiv 1512.09291)
Gaskell, C. M. & Ferland, G. J. 1984, PASP, 96, 393
Glikman, E., Helfand, D. J., White, R. L., et al. 2007, ApJ, 667, 673
Keel, W. C. 1980, ApJ, 85, 198
Khachikyan, E. Y. & Weedman, D. W. 1971, Astrophysics, 7, 231
Konigl, A., & Kartje, J. F. 1994, ApJ, 434, 446
Koski, A. T. 1978, ApJ, 223, 56
MacAlpine, G. M. 1981, ApJ, 251, 465
Osterbrock, D. E. 1977, ApJ, 215, 733
Osterbrock, D. E., & Ferland, G. J. 2006, Astrophysics of gaseous nebulae and active galactic nuclei, 2nd. ed. by D.E. Osterbrock and G.J. Ferland. Sausalito, CA: University Science Books, 2006
Peterson, B. M., Denney, K. D., De Rosa, G., et al. 2013, ApJ, 779, 109
Schmitt, H. R., Donley, J. L., Antonucci, R. R. J., et al. 2003, ApJ, 597, 768
Schuder, J. M., & MacAlpine, G. M. 1979, ApJ, 230, 348
Storey, P. J., & Hummer, D. G. 1995, MRAS, 272, 41
Tohline, J. E., & Osterbrock, D. E. 1982, ApJ, 252, L49
Valtonen, M. J. 1983, Ap&SS, 90, 207
Vanden Berk, D. E., Shen, J., Yip, C.-W., et al. 2006, ApJ, 131, 84
Wampler, E. J. 1968, ApJ Lett., 154, L53
Wysota, A., & Gaskell, C. M. 1988, Active Galactic Nuclei, 307, 79
Zheng, W., et al. 1995, AJ, 109, 6

© 2016 RAS, MNRAS 000, 1–?